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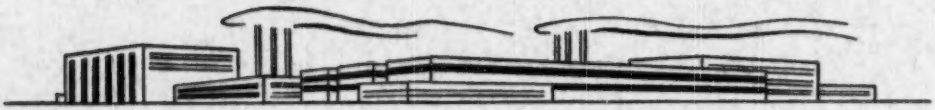

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TEXTILE RESEARCH JOURNAL

VOL. XX, No. 8 August, 1950

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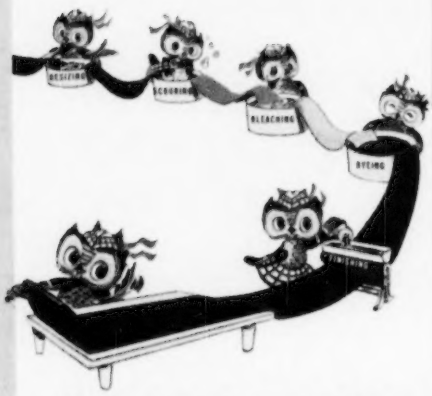

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TEXTILE RESEARCH JOURNAL

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Mechanics of Elastic Performance of Textile Materials

Part IV: Some Aspects of Stress Analysis of Textile Structures—Staple-Fiber Yarns*

Milton M. Platt

Fabric Research Laboratories, Inc., Boston, Massachusetts

Abstract

The study of the influence of textile geometry upon textile structure performance is extended to staple-fiber yarns. Methods previously developed for continuous-filament yarns [6] are applied to determine the theoretical dependency of staple-yarn tensile characteristics upon the stress distribution, and modifications thereof introduced by yarn twist, size, staple length, and inherent fiber properties. Both one-time loading to rupture and repeated-stress properties of acetate rayon and cotton yarns of various geometries are considered, and comparisons are made between experimental and theoretical data.

Introduction

This work, concerned with the elastic characteristics of staple-fiber yarns, follows as a logical extension of previously reported work [6] on similar properties of continuous-filament yarns. While from a military point of view the study of staple yarns is apparently of major importance (staple-fiber yarns are utilized in about 85% of service fabrics), the study of continuous-filament yarns was necessary and advantageous as a starting point (*a*) in order to establish sound testing techniques whereby the complicating variables of staple length and friction considerations would be kept at a minimum; (*b*) because continuous-filament yarns actually represent a special case of an infinitely long staple; (*c*) because the study of continuous-filament yarns, since they are simpler than staple-fiber yarns, has resulted in the development of working hypotheses which, as will be shown, aid in the understanding of staple-yarn characteristics.

The principal material being studied is acetate rayon, although it must be recognized that this

* Parts I and II of this series were published in the February and December, 1948, issues, respectively, and Part III in the January, 1950, issue of TEXTILE RESEARCH JOURNAL. Part V appears in this issue, page 539.

product serves purely as a convenient tool in the long-range phase of a research which is concerned with studying the influence of textile geometry on the translation of fiber properties into textile structures. Whenever practical from the point of view of time, the ideas developed are checked against other materials except where common knowledge and experience immediately indicate that such materials behave in a manner similar to that found for the acetate rayon.

It may be of advantage to discuss briefly the necessity for studying yarn characteristics since the ultimate use of fibers is made in the form of fabrics and not in yarns. Philosophically, it should be apparent that fibers find their way into conventional fabrics only in the form of yarns, and, unless proved otherwise, fabric characteristics should be more greatly dependent upon yarn characteristics than upon fiber characteristics. Hence, if fiber properties can be at all modified when the fibers are put into yarns, the necessity for studying yarns becomes apparent. From a practical standpoint, material in the literature demonstrates that the influence of changes in yarn construction on fabric properties can be important. Hamburger [2] and Hicks and Scroggie [4] showed that abrasion-resistance can be markedly influenced by such yarn geometrical parameters as filament denier, yarn denier, and yarn twist, even though inherent fiber properties are maintained constant. Gruntfest and Gagliardi [1] have indicated the importance of maintaining the multi-filamentous character of a yarn if a crease-resistant finish applied to a fabric is to be successful. In like manner, Schiefer *et al.* [7] have indicated yarn geometry to be important where such properties as "fabric assistance" are considered. Finally, it is obviously of advantage to determine whether and to what extent fabric properties are dependent upon yarn geometry, since even those results which indicate no interdependence serve to simplify this complicated problem.

As will be demonstrated in the main body of this report, the attainment of a rigorous mathematical treatment, such as has been developed for continuous-filament yarns [6], appears, because of extreme complications, to defy all effort for the case of staple-fiber yarns. However, this does not obviate either the compilation of useful quantitative data on the properties of staple yarns or the semi-quantitative explanation of the performance of staple yarns based partially upon continuous-filament yarn performance.

A. General

The study of the influence of textile geometry on textile performance becomes exceedingly complicated once staple-fiber yarns are brought into consideration. A multitude of reasons exist for this situation, two of the most important of which are:

1. Laboratory investigations of such inherent properties as fiber-to-fiber friction and its variation with mechanical considerations, such as pressure, strength, staple length, etc., have never been fully undertaken or successfully carried out.

2. The geometry of so seemingly simple a structure as a staple-fiber yarn is in reality a very complex one, markedly influenced by the method of manufacture.

As will be indicated later, both of the above considerations play an important part in textile performance, and therefore complete solutions to the problem of staple-yarn characteristics must await further studies. Nevertheless, it is possible to study the results of investigations of properties which are dependent on such variables as those mentioned above, and to rationalize these results on the basis of similar properties of continuous-filament yarns whose inherent fiber properties duplicate those of the staple-fiber yarns.

B. Materials Studied

1. Acetate Rayon—3 Denier per Filament, 300-Denier Yarns

It was planned to place the major emphasis of the work on this material. To that end, the same continuous-filament acetate tow previously studied [6] was cut to a variety of staple lengths which would include that corresponding to a long-staple cotton. Staple arrays indicated that, utilizing the processing equipment available at the time, only fiber lengths up to 2½ in. could be processed into yarn without severe stretching and, in some cases, without tensile rupture of some of the fibers. Longer fiber lengths produced staple arrays which were exceedingly non-uniform—*e.g.*, tow cut to 6 in. produced yarns whose arrays contained fibers of lengths from 0 to 8 in., the mean being approximately 3.75 in. Hence, only 1½-in. and 2½-in. staple yarns were studied. The arrays for the 1½-in. and the 2½-in. staple yarns (Figure 1) indicate the uniformity of fiber lengths within the processed yarns.

For both fiber lengths, yarns of 11.0, 15.0, 19.0, 23.0, and 27.0 turns per inch (t.p.i.) were spun.

As a check on the effects of processing on fiber properties, samples of fibers removed from the yarns were tested for their flat-bundle strengths, yielding the results shown in Table I.

Statistical analysis showed the difference between the three strengths in Table I to be insignificant, and it was concluded that substantially the same fibers exist in all 3 yarns. Hence, differences in yarn properties will exist only on the basis of differences in yarn geometry and not because of differences in inherent fiber properties.

II. Cotton

Conclusions for the acetate yarns have been checked against a non-pedigreed cotton yarn, 13.8's nominal cotton count, spun to various twists.

C. Effects of Yarn Geometry on Stress-Strain Characteristics

1. Continuous-Filament Yarns

It has been shown in previous work [6] that the elastic properties, including the rupture characteristics, of continuous-filament yarns are predictable once the inherent elastic characteristics of the fiber, the yarn size, and the yarn twist (surface helix angle) are known. Deviations in the elastic characteristics, under tensile load, of yarns with different geometries have been shown to arise purely as a result of changes in the stress distribution amongst the fibers because of the geometry.

The stress distribution is affected by twist in two ways, the first effect termed the "component effect" and the second the "serigraph effect."

The component effect refers to the fact that the axial tensile load on a yarn is the resultant, along the yarn axis, of the components of axial tensions

TABLE I. STRENGTHS OF FIBERS FROM YARNS

Yarn Staple Length	Flat-Bundle Strength*
2½ in.	0.460
1½ in.	0.480
Continuous filament	0.520

* Pounds of tensile strength per mg. of fiber weight, corrected to a 2-in.-long sample.

in the fibers. Since the sum of these components never can exceed the scalar sum of the fiber tensions, it is apparent that for two yarns with equal tensions the fibers in that yarn having the greater helix angle would be under more tension than the fibers in the yarn with the smaller helix angle. The higher the yarn twist the greater the fiber tensions for any given yarn load. The component effect is independent of the inherent properties of the fiber, depending only upon the yarn geometry.

The serigraph effect, on the other hand, depends upon inherent fiber properties for its magnitude, even though it arises as a result of yarn geometry. It inter-relates the effects of yarn geometry on the distribution of strains and stresses amongst the fibers. It has been shown [6] that when a yarn is extended any given amount the variation in strains amongst the fibers is such that the more inclined the fibers to the yarn axis (the greater the helix angle) the less the fiber strain and hence the less the fiber stress. While the variation in strains is fixed by the yarn geometry, the magnitude of the variation in stresses amongst the fibers is uniquely related to the basic elastic characteristics of the fibers as given by the shape of the stress-strain diagrams. The higher the tangent moduli to the stress-strain curve the greater the variation in stresses, and conversely.

The most important point to consider with respect to the serigraph effect in continuous-filament yarns, where the fibers lie in helical paths with little or no crimp, is that the yarn elongation at any load is the result of changes in the lengths of the fibers. Not only is this true for the elongations in a one-time loading to rupture of the yarn but it is also true for repeated stressing and the elastic constants obtained therefrom—*i.e.*, secondary creep, corrected residual elongation, elastic performance coefficient, etc. This, however, does not imply that any deformation of a singles continuous-filament yarn reflects a precisely equal fiber deformation. On the contrary, it has been shown [6] that the effect of twist on the elastic properties of continuous-filament yarns is dependent upon differentiating between

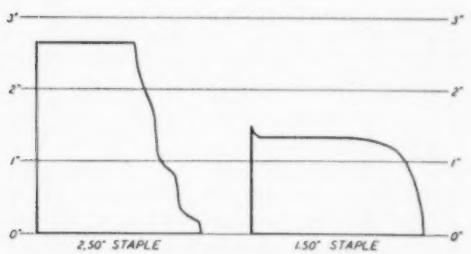


FIGURE 1 STAPLE ARRAYS OF ACETATE YARNS

yarn elongation and fiber elongations. The main point is that the elongation of any fiber is directly dependent upon and, moreover, proportional to, the yarn elongation, the constant of proportionality being the cosine or (cosine)^2 of the helix angle for elongation or strain (unit elongation), respectively (Figure 2). Hence, for continuous-filament yarns, yarn elongation reflects fiber elongation modified by yarn geometry. All yarn deformations result from rigid body deformations of the fibers. The situation is illustrated by the set of curves given in Figure 3. The use of these curves is explained by interpreting the meaning of the point marked "X" on the figure. This point signifies that if a multifilament yarn possesses a surface helix angle of 60° when the yarn is subjected to any given strain, say ϵ_y, then 40% of the total fibers in this yarn are strained between the limits of 0.45 ϵ_y and ϵ_y, while the remaining 60% of the fibers are strained between 0.25 ϵ_y and 0.45 ϵ_y, and similarly for other points.

While the curves in Figure 3 may be used as described above, they have been presented chiefly to emphasize that when a continuous-filament yarn is stretched, all the fibers which comprise the yarn are elongated in proportion to the yarn stretch, or, conversely, the elongation of fibers produces the yarn elongation. Hence, permanent set of fibers results in permanent set of the yarn, and similarly for the other criteria of elastic properties as indicated by the performance under repeated stressing.

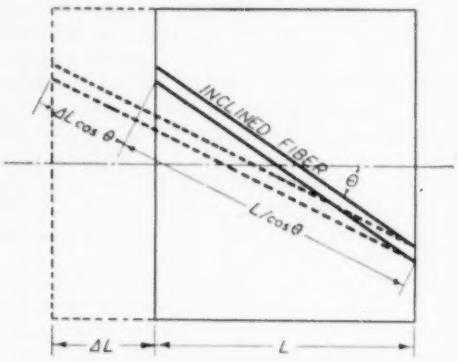


FIGURE 2 STRAINS IN TWISTED YARNS

A mathematical treatment of the foregoing has led to the following conclusions relevant to the effects of yarn form factors on the tensile properties of singles continuous-filament yarns:

(*a*) The major yarn form factors to be considered are the helix angles of the fibers in the yarn.

(*b*) The elongation to rupture of the most stressed fibers in yarns made of the same fiber is the same, regardless of yarn twists. For a uniform yarn geometry, wherein the fibers lie in the yarn in a true helix, with little or no crimp, this implies that yarn elongation to rupture is constant for singles yarns having different twist.

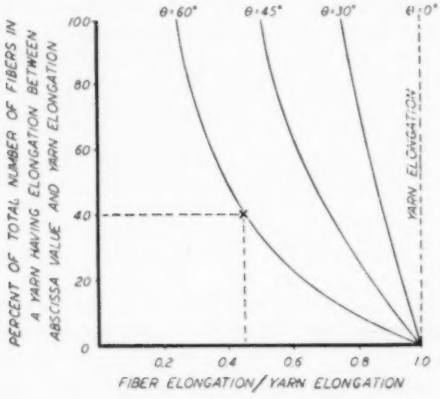
(*c*) At any strain, the following equation holds for the load being supported by the yarn:

$$P = 2\pi \int_{r=0}^{R} f \frac{r\,dr}{(1 + 4\pi^2 N^2 r^2)}, \qquad (1)$$

(P is yarn load, R is yarn radius, f is stress intensity in the yarn at distance r from yarn center, resulting from the strain, N is yarn twist). Equation (1), derived from static composition of forces, applies to any singles yarn, staple or continuous, and is independent of the nature of the fiber. Its applicability is limited only by the assumption of a uniform circular yarn whose fibers lie in perfect helices. Equation (1) is the analytic form of the "component effect."

FIGURE 3
DISTRIBUTION OF FIBER ELONGATION IN SINGLES CONTINUOUS FILAMENT YARNS

θ = THE AVERAGE HELIX ANGLE OF SURFACE FIBERS, AT THE YARN ELONGATION BEING COSIDERED



(*d*) The distribution of stresses, *f*, can be determined from the geometry of the yarn and the fiber stress-strain curve. Figure 2 shows how strains are distributed throughout the yarn in accordance with the fiber helix angles, and it is clear that from these strains and the stress-strain diagram of the yarn the stress distribution can be determined. In particular, when one is considering the loads at yarn rupture for a yarn whose fiber stress-strain diagram can be considered as approximately linear at rupture,* the stress distribution will be of the following form [6]:

$$f = \frac{A}{1 + 4\pi^2 N^2 R^2} + B, \qquad (2)$$

where all symbols have the same meaning as in equation (1) and A and B are constants for the fiber, determined from its stress-strain diagram. Equation (2) is a mathematical statement of the serigraph effect, and it is obvious from the foregoing that its magnitude depends upon the inherent properties of the fiber as well as upon the yarn geometry.

(*e*) Combination of the component and serigraph effects leads to the following parabolic equation for the relationship between yarn strength and yarn twist:

$$P = P_0 - K^2 N^2 R^2, \qquad (3)$$

where P_0 is the strength of the zero-twist yarn and K is a constant determined from the shape of the stress-strain curve for the fibers in the yarn. Strictly speaking, the form of equation (3) holds only when fibers are involved whose stress-strain diagrams are linear in the rupture region, but it can also be used for curve shapes other than linear ones when calculations need be only approximate.

(*f*) At corresponding loads below rupture, the elongation increases as the yarn twist increases.

(*g*) The energy absorption to rupture falls off parabolically with twist.

In the sections which follow, it will be shown that staple-fiber yarns exhibit the same general characteristics as those mentioned above, in the regions of twist greater than the optimum twist.

II. Staple-Fiber Yarns

When the stress-strain properties of staple-fiber yarn are considered, the situation becomes more complex for the following principal reasons:

(*a*) The basic yarn geometry is irregular in the sense that whereas the fibers in continuous-filament yarns can be considered to lie in perfect helical paths with little error, reports in the literature indicate a random entanglement of fibers in a staple yarn. Peirce has stated [5]: . . . "an effective geometry of yarn structure awaits the 'theory of the random tangle,' which has not yet been developed." Whether or not complete entanglement exists in staple-fiber yarns is not known, nor is it known that the magnitude of the effects of fiber entanglement is necessarily high—that is to say, while entanglement is necessary for cohesion, its effect on the other mechanical properties of yarns may not be great.

(*b*) The deformation present in staple-fiber yarns does not necessarily reflect the deformation in the fibers which compose those yarns. While it was previously indicated that for a continuous-filament yarn the elongation is the result of definite fiber elongations (*i.e.*, rigid body deformation), since each fiber is continuous from end to end of the yarn, a similar situation exists only in part for staple-fiber yarns.

(*c*) The types of deformation existing in staple-fiber yarns vary considerably with the gage length of the yarn. For continuous-filament yarns, changes in gage length affect the tensile characteristics only in accordance with whatever changes in rate of load or strain are involved, and also by the presence of weak spots in accordance with the theories of Peirce and others of the "weakest link."

Staple-fiber yarns are also subject to the above effects, but, in addition, one must consider the distribution of continuous *vs.* discontinuous fibers within the yarn. This factor is marked at low gage lengths, and would, of course, be representative of what occurs in a fabric, where the spacing of yarn intersections is of the order of magnitude of yarn diameter, and the cross-threads can act as "pseudo-jaws."

A semi-quantitative treatment of length effects may be made as follows:

(1) At essentially zero yarn length (very close jaw seperation), all of the fibers in the yarn cross section will be continuous from end to end of the yarn.

(2) At yarn lengths in excess of the staple length (a ratio of gage length to staple length in excess of 1), none of the fibers are continuous.

* This is the case for continuous-filament acetate and viscose when studied at constant rate of load. Nylon has a parabolic stress-strain curve in the rupture region.

(3) For gage lengths less than the staple length, the fractional number of discontinuous fibers would be proportional to the ratio $\frac{\text{gage length}}{\text{staple length}}$. This is obviously what would be expected, statistically, on the basis of a random spacial distribution of fiber lengths in a yarn, when the staple length is uniform.

Samples of cordage yarn, of approximately 45,000 denier, with about 120–150 fibers per yarn were examined at various gage lengths in order to determine whether the distribution of continuous and discontinuous fibers would actually comply with considerations (*a*), (*b*), and (*c*), above. Cordage yarns, since they are comprised of very large fibers, are easy to handle, and were found to be a convenient expedient for checking these considerations. The plots representing the distribution of fiber lengths are given in Graph 1, in which the two plots represent fiber which was cut to 40–50 in. by hand and fiber cut to 24–30 in. by hand also. It is clearly seen that for both yarns the following distribution laws exist:

$$C = 100\left(1 - \frac{\text{g.l.}}{\text{s.l.}}\right) \text{ for } \frac{\text{g.l.}}{\text{s.l.}} < 1 \qquad (4)$$

and

$$S = 100\left(\frac{\text{g.l.}}{\text{s.l.}}\right) \text{ for } \frac{\text{g.l.}}{\text{s.l.}} < 1, \qquad (5)$$

where C = % continuous fibers, S = % discontinuous fibers, g.l. = gage length, and s.l. = staple length.

For ratios of gage length to staple length greater than 1, $C = 0$ and $S = 100\%$. Equations (4) and (5) may be used in considering the strength of staple yarns at short gage lengths. If S_s is the strength contribution of a fiber in the discontinuous (staple) fiber phase and C_s is the strength contribution of a fiber in the continuous phase of a staple yarn having T total fibers in a cross section, it is apparent that:

GRAPH 1
EFFECT OF GAGE LENGTH ON DISTRIBUTION OF THROUGHGOING FIBERS

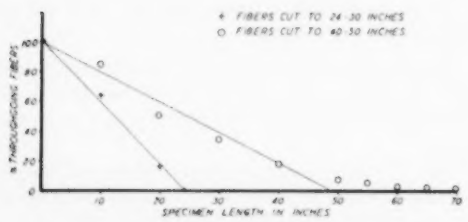
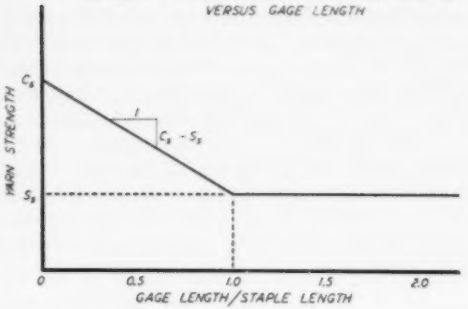


FIGURE 4 THEORETICAL STAPLE YARN STRENGTH VERSUS GAGE LENGTH

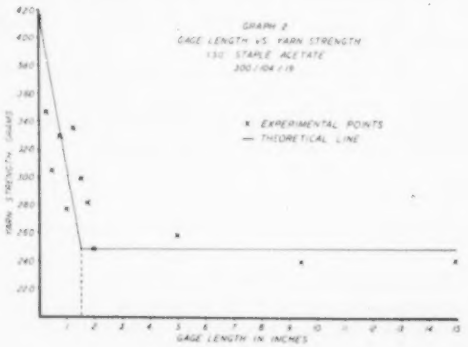


$$\text{Yarn strength} = C_s \times (\text{no. of continuous fibers}) + S_s \times (\text{no. of discontinuous fibers}) \qquad (6)$$

$$= C_s(T)\left(1 - \frac{\text{g.l.}}{\text{s.l.}}\right) + S_s(T)\left(\frac{\text{g.l.}}{\text{s.l.}}\right) \qquad (7)$$

$$= T\left[C_s - (C_s - S_s)\frac{\text{g.l.}}{\text{s.l.}}\right]. \qquad (8)$$

The quantity C_s represents the *inherent* strength of a single fiber, while S_s represents the strength imparted by a single fiber as it exists in a staple-fiber yarn—*i.e.*, the maximum friction per fiber. Equation (8) states that a plot of staple-yarn strength *vs.* gage length should be composed of two straight lines, as shown diagrammatically in Figure 4. In Graph 2 is given experimental verification of equa-



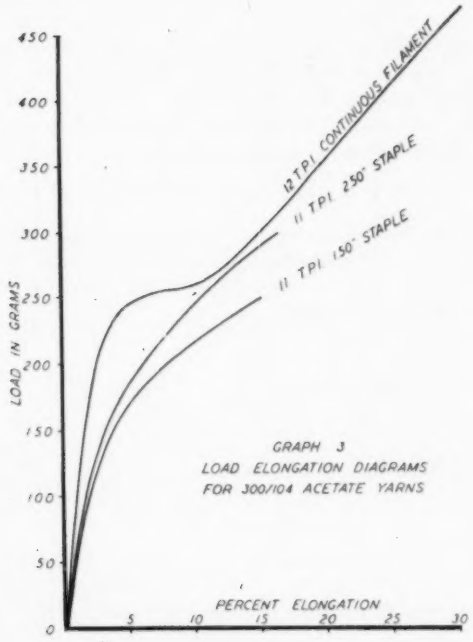
tion (8). Here, all points, except that for 0 gage length, were experimentally determined as the average of 25 breaks per point. The point at 0 gage length was calculated from an equation previously given [6] for continuous-filament yarn strengths. The two straight lines represent the theoretical curve obtained from equation (8) and the yarn staple length. Spot checks were also made of the strength of 300/104 continuous-filament acetate yarn with both 12.0 and 24.0 t.p.i. at gage lengths of ½ in., 5 in., and 20 in., and the over-all loss in strength from low to high gage length was of the order of only 4%–6%.

When load is applied to a staple-fiber yarn, every filament is stressed in accordance with whatever stress distribution exists within the yarn cross section, and hence strains compatible with these stresses must also exist. However, since fibers are joined longitudinally to other fibers only as the result of frictional forces, it is apparent that the sliding of fibers past each other increases the total elongation at a given load beyond that which would obtain if only inherent fiber elongation were considered. In other words, the total elongation at a given load for a staple-fiber yarn is the result of the following two factors:

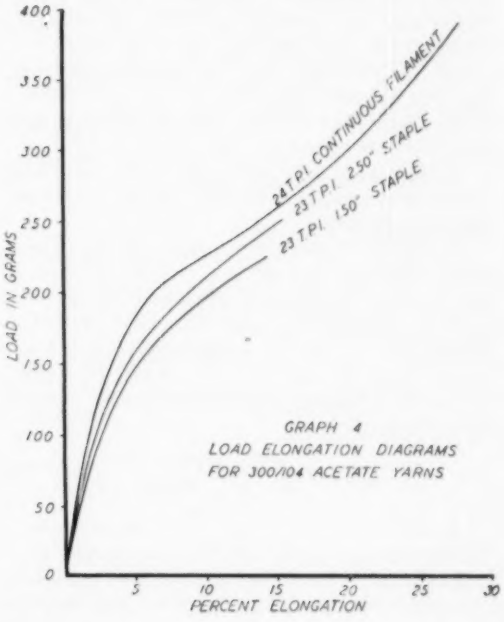
(1) Rigid Body Deformation: This is the actual elongation of the fibers within the yarn, which depends upon load and yarn twist in the same general manner as is the case for fibers in a continuous-filament yarn.

(2) Rigid Body Translation: Simultaneous with extension of the fibers under a given tensile load there is an actual movement of the fibers past each other whenever the force (tension) which must be transmitted longitudinally from one fiber to another exceeds the maximum friction force capable of being developed by the overlap between fibers. The slippage characteristics depend upon the magnitude of the tensile load on the yarn, the yarn twist, the fiber staple length, the gage length of the test specimen, the number and type of points of contact between fibers, and the coefficient of friction.

Graphs 3 and 4 illustrate the effect of staple length on the slippage. Here are shown the stress-strain diagrams of both the continuous-filament and the staple-fiber acetate yarns of 12 and 24 t.p.i. For both twists, it can be seen that at any given



GRAPH 3
LOAD ELONGATION DIAGRAMS
FOR 300/104 ACETATE YARNS



GRAPH 4
LOAD ELONGATION DIAGRAMS
FOR 300/104 ACETATE YARNS

load, the elongation increases with decrease in staple length. The difference in elongations amongst the yarns reflects differences in slippage, and, as would be anticipated, the longer staple, since it possesses a greater degree of overlap of the fibers, shows less slippage than the shorter staple.

D. Stress Analysis of Staple-Fiber Yarns

I. Geometry

The complexities of staple-yarn geometry have already been discussed. The stress analysis of the structure, however, demands the assumption of a geometry which it is possible to handle mathematically. Hence, the following assumptions of geometrical form of the yarn will be made, with recognition of the fact that the picture presented is ideal. It remains for comparison between theoretical and experimental results to determine whether deviations of the ideal from the actual geometry seriously impair the utility of the results. The following assumptions will be made:

(*a*) The yarn is uniform along its length, and its cross-sectional outline is circular.

(*b*) All fibers within a yarn possess the same properties, and are circular in cross section.

(*c*) The center line of each fiber lies in a perfect helix, with the center of the helix located at the center of the yarn cross section.

(*d*) The fibers fall into a rotationally symmetric array in cross-sectional view.

(*e*) The diameter of the yarn is large compared with the fiber diameter.

These assumptions are exactly the same ones which were made for the analysis of continuous-filament yarns [6].

As has been previously stated, the component effect, described by equation (1), is independent of the nature of the fiber and whether or not the yarn is made of continuous filaments or staple fibers; it depends only upon the geometrical array of fibers in the yarn. Hence, equation (1) may be applied to staple yarns, and is repeated below as equation (9):

$$P = 2\pi \int_0^R \frac{f\, r\, dr}{1 + 4\pi^2 N^2 r^2}. \qquad (9)$$

As was the case for continuous-filament yarns, it is indicated by equation (9) that, for staple yarns, when the same axial yarn tension P is applied to two yarns the one having the higher twist will be subjected to the greater fiber tensions (f). Similarly, for equal fiber tensions, the yarn of higher twist will be supporting the lower yarn tension (P).

The yarn geometry giving rise to equation (9) is illustrated in Figure 5.

II. Analysis of Strains

From what has already been discussed, it is clear that in so far as staple yarns are concerned the concept of fiber strains, ordinarily considered to be change in length between two gage marks a unit distance apart along the fiber axis, must be modified to include fiber slippage. Only in the case of staple yarns of zero gage length is it possible for a change in yarn length to be associated with true fiber strain. For actual staple yarns, fiber strains must be associated with the total separation in length of two points located at different positions along the length of the yarn, but always along the same helical path at any given yarn cross section. The fiber strain can then be defined as equal to this separation per unit original length. The original length would, of course, exceed the staple length of the fibers. Under these conditions, then, fiber strain would consist of true fiber strain plus fiber slippage.

As a result of the foregoing definition of fiber strains in staple-fiber yarns, the distribution of strains amongst the fibers when the yarn is strained will duplicate that given in Figure 2 for continuous-filament yarns. Thus, the strain in any fiber, when the yarn strain is ϵ_y, can be written as:

$$\epsilon_f = \epsilon_y \cos^2\theta = \epsilon_y / 1 + 4\pi^2 N^2 r^2, \qquad (10)$$

where θ is the helix angle of the fiber being considered. It is emphasized that both ϵ_f and ϵ_y consist not only of changes in length but also of slippage of the fiber.

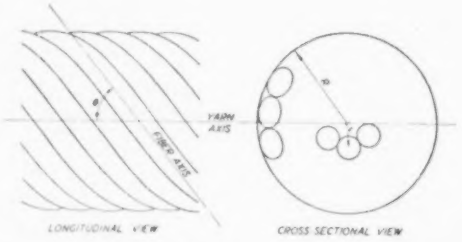


FIGURE 5 IDEALIZED GEOMETRY OF SINGLES YARN

III. Analysis of Stresses

For the case of continuous-filament yarns, the next step in the analysis is to consider any yarn elongation, ϵ_y, and the specific yarn elongation at rupture, ϵ_{yr}. Then, equation (10) would define the strain at any point r from the yarn center in terms of N, the yarn twist. The stress-strain curve of a fiber (or zero-twist yarn) then gives the analytic expression for stress in terms of strain, and, hence, it is now possible to formulate the stress in terms of r and N. The resulting expression for f is then substituted into equation (9), which can then be integrated to give a formula for the yarn tensile load in terms of yarn radius, R, and yarn twist N. It can be shown that for a yarn with a linear stress-strain curve near rupture, similar to that shown in Figure 6, the result of such an analysis is as follows:

If the load-elongation diagram of the fiber or zero-twist yarn can be written as:

$$P_0 = fA = a + b\epsilon_0, \tag{11}$$

where P_0 is the load on the fiber or zero-twist yarn for an elongation of ϵ_0, then:

$$P_N = \frac{\pi}{A}\left[\frac{a}{(4\pi^2N^2)}\ln(1 + 4\pi^2N^2R^2) + b\epsilon_y\frac{R^2}{1 + 4\pi^2N^2R^2}\right], \tag{12}$$

where P_N is the load on yarn of N turns per unit length when the yarn elongation is ϵ_y. Equation (12) can be simplified by expansion of both terms into a power series:

$$P_N = a(1 - 2\pi^2N^2R^2) + b\epsilon_y(1 - 4\pi^2N^2R^2), \tag{13}$$

or, at rupture where $\epsilon_y = \epsilon_{yr}$, and $P_{or} = a + b\epsilon_{or}$,

$$P_{Nr} = P_{or} - \pi^2N^2R^2(2a + 4b\epsilon_{or}). \tag{14}$$

Equations (12) and (13) represent the equation for the load-elongation diagram near rupture for a yarn with N turns, made from a fiber or zero-twist yarn whose load-elongation diagram is given in equation (11). It is apparent that the introduction of twist has left unchanged the linearity of the equation for the load-elongation diagram. However, examination of the factors by which a and $b\epsilon_y$ are multiplied in equations (12) and (13) indicates that both the intercept a and the slope b have been reduced, so that the load-elongation diagram of the high-twist yarn would be positioned differently from that of the zero-twist yarn. However, it is possible by equations (12) and (13) to correct both a and b, calculated from a curve for a high-twist yarn, to those of the same yarn with zero twist, as follows:

$$a_0 \text{ (for zero-twist yarn)} = \frac{a_N \text{ (for yarn of any twist)}}{(1 - 2\pi^2N^2R^2)} \text{ (series expansion)},$$

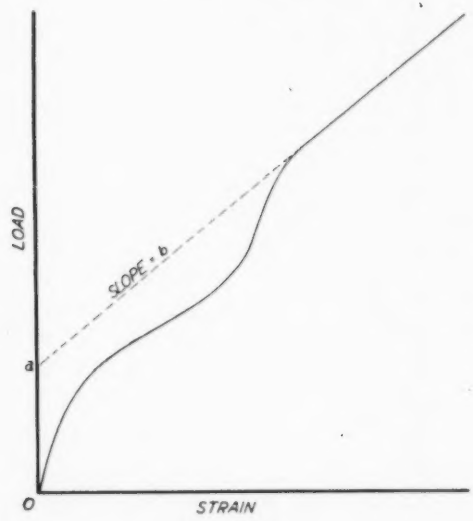
$$a_0 \text{ (for zero-twist yarn)} = \frac{a_N \text{ (for yarn of any twist) } 4\pi^2N^2R^2}{\ln(1 + 4\pi^2N^2R^2)} \text{ (exact expression)}, \tag{15a}$$

$$b_0 \text{ (for zero-twist yarn)} = \frac{b_N \text{ (for yarn of any twist)}}{1 - 4\pi^2N^2R^2} \text{ (series expansion)},$$

$$b_0 \text{ (for zero-twist yarn)} = b_N \text{ (for yarn of any twist)} \times (1 + 4\pi^2N^2R^2) \text{ (exact)}. \tag{15b}$$

In the case of continuous-filament yarns, correction factors such as those given by equations (15) are not necessary, since it is always possible to

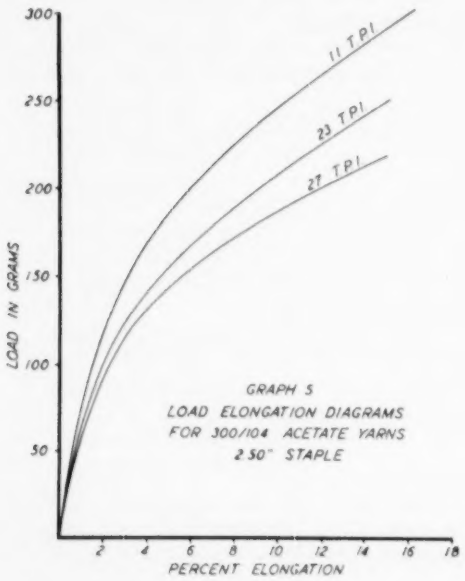
FIGURE 6 HYPOTHETICAL STRESS STRAIN CURVE OF A FIBER OR A ZERO TWIST YARN



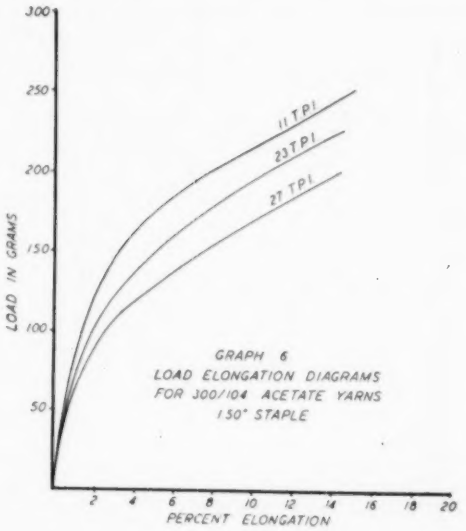
experimentally determine the load-elongation diagram of either a fiber or a zero-twist yarn. However, for staple-fiber yarns, it is clear that to test a fiber would be to completely ignore the slippage effect, whereas to rupture a zero-twist yarn would be to neglect any cohesion introduced by twisting. Hence, as will be discussed later, in order to obtain numerical results for staple yarns the correction factors of equations (15) *must* be used.

Equation (14) expresses yarn strength in terms of yarn twist. Its applicability to staple-fiber yarns will be described later.

With the foregoing concepts and methodology described for continuous-filament yarns, it is of interest to inquire into their applicability to staple-fiber yarns. This has already been partially done by the discussion relating to the use of the correction factors given by equations (15). However, there is involved in the use of equations (14) and (15) for staple yarns a concept which should be further expanded. By correcting back to a zero-twist yarn, a hypothetical structure is involved which is of pertinent interest. This hypothetical yarn would therefore be a staple yarn possessing the same cohesion between fibers as high-twist yarns possess by virtue of their twist, but with no twist present. In other words, it is necessary to picture the friction afforded by twist to be produced by, say, a cementing material between fibers, the elastic characteristics of which duplicate those of whatever friction forces are produced by the twist. Thus, the yarn would possess the same cohesion as that produced by twist, but not at the expense of changes in strength or elastic characteristics due to obliquity of the fibers. It is this imaginary yarn which would have the strength P_0 indicated by equation (14). It becomes immediately apparent, then, from equation (14), which requires that strength decrease continually with twist, that only twists above the optimum are to be considered. Furthermore, equation (14) indicates that if P_{N_T}, the strength of any one yarn of twist greater than optimum, is known, as are a and b, then it is possible to solve for P_{or}, the strength of the zero-twist yarn whose cohesion would be the same as that of the high-twist yarn. Equation (14) then requires that independent of what yarn twist is considered, just so long as it is above optimum, the fiber-to-fiber cohesion would be the same. In other words, at twists higher than the optimum no further cohesion is attained by further increases in yarn twist. This would have to be the case if P_{or} remained constant with twist beyond the optimum. As will be seen from the experimental results and discussion, this situation is realized rather well for both the staple acetate yarns and the cotton yarns studied, and, therefore,



GRAPH 5
LOAD ELONGATION DIAGRAMS
FOR 300/104 ACETATE YARNS
2.50" STAPLE



GRAPH 6
LOAD ELONGATION DIAGRAMS
FOR 300/104 ACETATE YARNS
1.50" STAPLE

by the use of equations (14) and (15) it becomes possible to predict the strengths of singles staple yarns of twist beyond the optimum if the load-elongation diagram of any one yarn beyond optimum twist is known.

To recapitulate the procedure for staple yarns and its limitations:

(*a*) Determine the load-elongation diagram for a staple yarn whose twist exceeds the optimum. If in the region near rupture the diagram can be approximated as linear, determine the intercept a and the slope b of the curve.

(*b*) Using equation (15), correct a and b, so found, back to a zero-twist yarn. This establishes the load-elongation diagram near rupture for a hypothetical zero-twist yarn whose cohesion duplicates that of all yarns of twist greater than the optimum.

(*c*) From equation (14), knowing P_{Nr}, the strength of the yarn whose load-elongation diagram was determined in (*a*) above, and the quantities a and b, it is possible to calculate P_{or}, the strength of the hypothetical zero-twist yarn. This strength, P_{or}, physically represents the total scalar cohesion introduced by twist, which cohesion is assumed to be constant with twist for twists equal to or greater than the optimum.

IV. Application to Acetate Rayon

In Graphs 5 and 6 are shown representative load-elongation diagrams, for different yarn twists, of 2½-in. and 1½-in. staple acetate yarns, respectively. It is to be noted from these graphs that, as yarn twist increases, the elongation at a given load also increases. In addition, it can be seen that, as predicted by equation (15), both the intercept and the slope of the load-elongation diagram near rupture decrease with increase in yarn twist. All the curves can be represented as approximately linear in the region near rupture.

For the calculations which follow, it will be assumed that only the load-elongation diagrams of the staple acetates having 11.0 (nominal) t.p.i. are known, and the strengths of higher-twist yarns will be calculated. In addition to those for the 2½-in. and 1½-in. staple, calculations were performed for nominal 6-in. and 3½-in. staple acetate, both of which showed severe fiber rupture during processing. The calculations for 1½-in. staple are shown in Table II.

TABLE II. 1½-INCH STAPLE ACETATE—300 DENIER—11.0 TURNS PER INCH, NOMINAL TWIST

$R^2 = 18 \times 10^{-6}$ sq. in.*

$\epsilon_{Nr} = 0.15$ in./in.

Equation of load-elongation diagram (11.0 t.p.i. yarn):

$$P_N = 138 + 750\,\epsilon_N.$$

$$\therefore \quad a_N = 138; \qquad b_N = 750.$$

Correcting a and b back to zero-twist yarn:

$$a_0 = \frac{138}{(1 - 2\pi^2 N^2 R^2)\dagger} = \frac{138}{(1 - 0.032)} = 142;$$

$$b_0 = \frac{750}{1 - 4\pi^2 N^2 R^2} = \frac{750}{1 - 0.064} = 800.$$

$$\therefore \quad P_{Nr} = P_{or} - (2a_0 + 4b_0\epsilon_{Nr})\pi^2 N^2 R^2 = P_{or} - 764\pi^2 N^2 R^2.$$

P_{Nr} for 11 t.p.i. yarn = 257 g.

$$\therefore \quad P_{or} = 257 + 764\pi^2 N^2 R^2 = 257 + 12 = 269 \text{ g.}$$

$$\therefore \quad P_{Nr} = 269 - 764\pi^2 N^2 R^2.$$

* The square of the yarn radius at rupture (see [6]).

† N = Yarn twist at rupture (see [6]).

Yarn twist (t.p.i.)	$764\pi^2 N^2 R^2$	P_{Nr} (g.)	P_{Nr} (experimental) (g.)
11.0	12	257	257 ± 14*
15.0	23	246	258 ± 14
19.0	39	230	248 ± 13
23.0	55	214	235 ± 10
27.0	72	197	198 ± 14

The same procedure as shown in Table II was used for 2½-in., 3½-in., and 6-in. staple yarns. The results are shown in Graph 7, where experimental strengths, each the average of 25 tests, are plotted against yarn twist. These experimental data are shown as a shaded area, the vertical displacement representing the mean experimental strengths plus and minus two standard errors, which range gives the statistical limits within which the mean can fall

* ± Values represent two standard errors of mean experimental yarn strengths.

GRAPH 7
CALCULATED AND EXPERIMENTAL YARN STRENGTH VS. YARN TWIST FOR 300/104 ACETATE

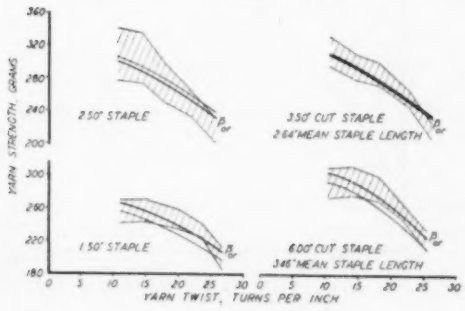


TABLE III. VALUES OF P_{or} FOR 300-DENIER STAPLE ACETATE YARNS

Nominal twist (t.p.i.)	1½-in. (g.)	2½-in. (g.)	3½-in. (g.)	6-in. (g.)
11.0	269	324	330	310
15.0	281	330	326	327
19.0	287	316	335	333
23.0	290	309	328	327
27.0	270	298	312	319
$\bar{P}_{or}$	279	315	326	323
Standard deviation	9.0	12	8.6	8.9
Coefficient of variation	3.2%	3.8%	2.6%	2.8%

at the 5% probability level. The unlabeled solid lines represent the calculated strengths. The lines labeled $\bar{P}_{or}$ will be discussed later.

It can be seen from Graph 7 that good agreement has been obtained between calculated and experimental points. In no case did the calculated value differ from the experimental mean by more than 10%. With respect to the statistical limits of experimental values, the maximum difference between calculated and observed strengths is no greater than 5%, and this for only 2 points out of a possible 20.

It is now of interest to inquire into the constancy of P_{or} with twist increases beyond the optimum. It could be anticipated, since good agreement was obtained between calculated and experimental strengths, that P_{or} would be fairly constant. However, it is of value to note whether a trend exists for P_{or} with increase in twist beyond the optimum. The values of P_{or} are, of course, calculated from the experimental strengths P_{Nr} and the theoretical losses in strength, $(2a_0 + 4b_0\epsilon_{yr})\pi^2N^2R^2$. The data are summarized in Table III.

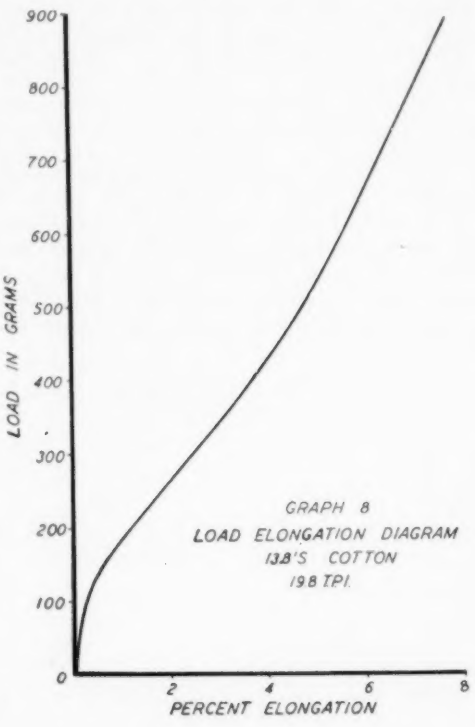
It can be seen from Table III that within a given staple length the values of P_{or} are fairly constant. The coefficients of variation for the various yarns are small. When it is recognized that experimental strengths, each having its own coefficient of variation of about 15%, were used directly in obtaining the values of P_{or} shown in Table III, the constancy of P_{or} becomes more apparent.

If P_{or} is constant with twists beyond the optimum, then it is clear that a statistically better twist-strength curve could be obtained for each staple length by using the values $\bar{P}_{or}$ shown in Table III rather than the value of P_{or} corresponding to the 11.0 t.p.i. yarns. When this is done, the lines labeled $\bar{P}_{or}$ on Graph 7 are obtained. It is immediately apparent that this new curve agrees excellently with the experimental data. This would be expected since the use of an average P_{or}, as it is based on a large statistical sample, would be a better statistical mean. However, for all practical purposes, sufficiently precise results can be obtained merely by determining P_{or} for the 11.0 t.p.i. yarns.

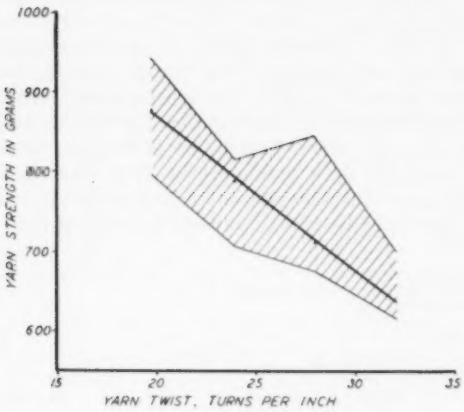
V. Application to Cotton Yarns

To test the applicability of the methods to cotton yarns, a series of nominal 13.8's yarns were spun from the same roving to various twists up to 32.0 t.p.i. The average load-elongation diagram for the yarn having 19.8 t.p.i. is shown in Graph 8. For the size of this yarn and the magnitude of twists involved, it can easily be ascertained that the series expansions, equations (14) and (15), would not be sufficiently accurate for use here. Hence, the more precise equation (12) is used.

From Graph 8, the equation of the linear portion



GRAPH 9
CALCULATED AND EXPERIMENTAL
YARN STRENGTH VS. YARN TWIST
FOR 12.5'S COTTON



of the load-elongation diagram is obtained as:

$$P_0 = fA = a + b\epsilon_0 = -75 + 12{,}500\,\epsilon_0.$$

Using equation (15), it is clear that:

$$a_0 = a_N \frac{4\pi^2N^2R^2}{\ln(1 + 4\pi^2N^2R^2)} = \frac{-75 \times 0.289}{0.254} = -85.5$$

and

$$b_0 = b_N(1 + 4\pi^2N^2R^2) = 12{,}500 \times 1.289 = 16{,}100.$$

The values a_0 and b_0 are the intercept and the slope, respectively, for the imaginary zero-twist yarn.

The equation for strength then becomes (equation (12)):

$$P_{Nr} = \frac{1{,}225}{(1 + 4\pi^2N^2R^2)} - 85.5\,\frac{\ln(1 + 4\pi^2N^2R^2)}{4\pi^2N^2R^2};$$

$$P_{\infty r} = \lim_{N\to\infty} P_{Nr} = 1{,}225 - 85.5 = 1{,}140 \text{ g.}$$

Yarn twist (t.p.i.)	P_{Nr} Calculated strength (g.)	P_{Nr} Experimental strength (g.)
19.8	875	870 ± 72*
24.0	789	760 ± 54
28.0	711	760 ± 85
32.0	636	660 ± 43

When the calculated and experimental strengths are plotted against twist, the excellent agreement shown in Graph 9 is obtained. Here again the results indicate constant $P_{\infty r}$, so that once optimum twist is reached no additional cohesion is afforded the yarn by further twist increases.

It is interesting to consider the strength losses which occur because twist is inserted into this cotton yarn. The maximum strength obtained is 870 g., at a twist of 19.8 t.p.i. The value of $P_{\infty r}$ of 1,140 g. indicates that had the same cohesion existed without twist the strength would be 1,140 g., an increase of 31%. In other words, the cohesion attainable by 19.8 t.p.i. has been penalized 270 g. because of the inclination of the fibers resulting from this twist.

* Two standard errors.

E. Elastic Characteristics of Staple-Fiber Yarns

The foregoing discussion on the stress-strain characteristics of yarns with different geometry (*i.e.*, different twist and staple length) serves as background for understanding the effects of yarn geometry on elastic characteristics as evidenced by the repeated-stress properties of yarns.

The effects of yarn twist on the repeated-stress characteristics of continuous-filament yarns have already been described, and the results explained and correlated with fiber properties [6]. For purposes of convenience the following definitions are given, followed by a summary of those results which have already been reported:

1. Definitions

(*a*) *Mechanical conditioning*—The process of cyclical loading and unloading at a constant rate between zero load and some maximum load, the cycles being of sufficient number so that the last hysteresis loop is imperceptibly different from the next previous one. It is usually found that 5 cycles of repeated loading are sufficient for mechanical conditioning.

(*b*) *Conditioning load*—The maximum load (upper reversal point) in the process of mechanical conditioning.

(*c*) *Conditioned cycle*—The last cycle—*i.e.*, one which differs imperceptibly from the previous one.

(*d*) *Secondary creep* (%)—The permanent set of a material as evidenced by the residual deformation at the start of the conditioned cycle, expressed as a percent of the original gage length.

(*e*) *Corrected residual elongation* (%)—The elongation to rupture of a mechanically conditioned sample, calculated as a percent of the sum of original gage length and secondary creep.

(*f*) *Elastic performance coefficient*—A normalized index of the degree of perfect elasticity exhibited by a material, calculated on the basis of the similarity in amount and rate of energy absorption and return between an unconditioned and a mechanically conditioned specimen.

II. Summary of Elastic Characteristics of Singles Continuous-Filament Yarns

In order to predict and/or explain the influence of yarn twist on the repeated-stress characteristics of singles continuous-filament yarns, it is first necessary to determine the effects of the magnitude of the conditioning load on the elastic properties of either the fiber or a yarn with essentially zero twist. Changes in elastic properties with changes in yarn geometry are primarily the result of changes in stress distribution. For the acetate rayon studied in this research, the following elastic characteristics were observed:

(*a*) Above the yield point, the higher the conditioning load the greater the secondary creep and the less both the corrected residual elongation and the elastic performance coefficient for yarns with essentially zero twist. Close to the yield point, small changes in the conditioning load produce large changes in the afore-mentioned properties, while at higher loads the changes are smaller. These obser-

TABLE IV. REPEATED-STRESS PROPERTIES OF 1½-INCH STAPLE ACETATE YARNS; CONDITIONING LOAD = 125 GRAMS*

Yarn twist (t.p.i.)	Secondary creep (%)	% Std. dev.	Corrected residual elongation (%)	% Std. dev.	Elastic performance Coeff.	Std. dev.	Energy to rupture (in.-lb./in.)	Std. dev.
11.0	1.74	0.46	15.8	4.12	0.481	0.036	0.063	0.020
15.0	1.83	0.65	14.4	4.57	0.476	0.066	0.058	0.026
19.0	2.21	0.89	13.3	4.99	0.497	0.076	0.050	0.023
23.0	2.22	0.36	12.9	3.91	0.486	0.101	0.045	0.019
27.0	3.47	1.07	11.0	3.38	0.378	0.066	0.042	0.014

* All values average of 10 tests, except 19.0 and 23.0 t.p.i. values, which are averages of 21 tests.

TABLE V. REPEATED-STRESS PROPERTIES OF 2½-INCH STAPLE ACETATE YARNS; CONDITIONING LOAD = 125 GRAMS*

Yarn twist (t.p.i.)	Secondary creep (%)	% Std. dev.	Corrected residual elongation (%)	% Std. dev.	Elastic performance Coeff.	Std. dev.	Energy to rupture (in.-lb./in.)	Std. dev.
11.0	0.15	0.26	18.2	3.31	0.829	0.102	0.066	0.025
15.0	0.11	0.28	17.4	4.71	0.805	0.113	0.087	0.038
19.0	0.29	0.34	18.0	3.91	0.807	0.141	0.084	0.024
23.0	0.47	0.49	12.5	5.11	0.859	0.175	0.056	0.027
27.0	0.95	0.73	11.5	3.91	0.686	0.117	0.043	0.019

* All values average of 20 tests except 23.0 and 27.0 t.p.i. values, which are averages of 15 tests.

TABLE VI. REPEATED-STRESS PROPERTIES OF 1½-INCH STAPLE ACETATE YARNS; CONDITIONING LOAD = 175 GRAMS*

Yarn twist (t.p.i.)	Secondary creep (%)	% Std. dev.	Corrected residual elongation (%)	% Std. dev.	Elastic performance Coeff.	Std. dev.	Energy to rupture (in.-lb./in.)	Std. dev.
11.0	4.87	1.4	12.7	4.9	0.343	0.09	0.058	0.022
15.0	5.50	2.4	13.2	6.0	0.326	0.09	0.051	0.031
19.0	7.15	1.4	7.0	2.1	0.256	0.05	0.029	0.014
23.0	7.61	1.7	7.82	2.8	0.252	0.04	0.029	0.015
27.0	9.37	1.8	6.25	1.3	0.212	0.04	0.021	0.006

* All values average of 10 tests.

vations describe inherent properties of the acetate fiber, and explain the effects of yarn twist on changing these elastic characteristics.

(*b*) The higher the yarn twist the greater the secondary creep and the smaller both the corrected residual elongation and the elastic performance coefficient for a given conditioning load. All three properties when plotted *vs.* yarn twist produce parabola-shaped curves [6]. It is also to be noted that the degree of difference in these properties with respect to differences in yarn twist is greater in general at loads close to the yield point than at higher loads.

All the effects noted in (*b*) above are the result of the non-uniformity of stress amongst the fibers and the changes in this non-uniformity with yarn twist, both of which are predictable from fiber properties and yarn geometry. From (*a*) above, the effect of increased load supported by the filaments is apparent. Since, as was previously discussed, higher yarn twists produce greater filament stresses for a given yarn load, then the effects given in (*b*) follow.

III. Staple-Fiber Yarns

As was the case for the stress-strain curves, already discussed, the manner in which and the extent to which staple length alters the translation of the fiber elastic properties depend upon the

TABLE VII. REPEATED-STRESS PROPERTIES OF 2½-INCH STAPLE ACETATE YARNS; CONDITIONING LOAD = 175 GRAMS *

Yarn twist (t.p.i.)	Secondary creep (%)	Secondary creep % Std. dev.	Corrected residual elongation (%)	Corrected residual elongation % Std. dev.	Elastic performance Coeff.	Elastic performance Std. dev.	Energy to rupture (in.-lb./in.)	Energy to rupture Std. dev.
11.0	3.32	2.9	13.9	5.8	0.563	0.23	0.071	0.041
15.0	2.28	2.2	13.8	4.7	0.583	0.20	0.069	0.032
19.0	3.36	2.5	14.8	5.6	0.470	0.20	0.059	0.029
23.0	3.84	2.1	10.6	3.7	0.441	0.13	0.045	0.023
27.0	5.50	1.4	8.32	2.6	0.342	0.06	0.032	0.013

* All values average of 16 tests.

TABLE VIII. REPEATED-STRESS PROPERTIES OF 1½-INCH STAPLE ACETATE YARNS; CONDITIONING LOAD = 200 GRAMS *

Yarn twist (t.p.i.)	Secondary creep (%)	Secondary creep % Std. dev.	Corrected residual elongation (%)	Corrected residual elongation % Std. dev.	Elastic performance Coeff.	Elastic performance Std. dev.	Energy to rupture (in.-lb./in.)	Energy to rupture Std. dev.
11.0	8.43	2.38	8.35	3.74	0.258	0.065	0.041	0.021
15.0	8.09	2.36	9.95	4.37	0.243	0.043	0.048	0.029
19.0	9.84	1.32	6.50	1.83	0.219	0.030	0.027	0.010
23.0	11.50	1.57	5.54	1.66	0.239	0.104	0.019	0.003
27.0	11.52	0.69	5.61	1.33	0.188	0.022	0.019	0.007

* All values average of 10 tests.

TABLE IX. REPEATED-STRESS PROPERTIES OF 2½-INCH STAPLE ACETATE YARNS; CONDITIONING LOAD = 200 GRAMS *

Yarn twist (t.p.i.)	Secondary creep (%)	Secondary creep % Std. dev.	Corrected residual elongation (%)	Corrected residual elongation % Std. dev.	Elastic performance Coeff.	Elastic performance Std. dev.	Energy to rupture (in.-lb./in.)	Energy to rupture Std. dev.
11.0	4.63	2.62	13.3	4.19	0.467	0.193	0.074	0.032
15.0	3.68	1.54	13.3	4.46	0.467	0.109	0.067	0.029
19.0	5.41	3.50	11.6	4.87	0.385	0.153	0.061	0.033
23.0	5.13	1.95	9.14	3.07	0.341	0.035	0.043	0.019
27.0	8.04	2.62	5.73	1.57	0.275	0.066	0.021	0.009

* All values average of 10 tests.

effects of the geometry on fiber slippage. These effects have already been inferred in the discussion relevant to the effects of twist and staple length as they affect the yarn elongation at a given load.

The data covering the repeated-stress properties of both 1½-in. and 2½-in. staple acetate yarns are given in Tables IV–IX inclusive. Standard deviations are also given in these tables, together with the number of tests made to yield the averages shown. The number of tests employed was dependent upon the estimated number required to produce a reliable mean—*i.e.*, the greater the variability in values the greater the number of tests.

Cursory examination of the data given in the tables will show the high variability in the repeated-stress properties. The coefficients of variation for all of the work have been considerably larger for the staple-fiber yarns than for the continuous-filament yarns. Such effects as variations introduced by the additional manufacturing operations required for staple-fiber yarns are an important cause for the high variability. Also the intimate dependency of the mechanical properties of staple yarns upon friction, itself a variable property, can produce high variation in yarn properties.

Statistical analyses have not been performed on the data for the following reasons: (1) A limited number of frequency-distribution analyses have indicated the population represented by the data to be decidedly abnormal, the frequency diagrams exhibiting a considerable amount of skew. Hence, conventional methods for determination of the significance of differences could not be used. (2) It is felt that the data are of sufficient number, the empirical trends sufficiently evident, and the direction of the trends sufficiently logical that even were the data capable of statistical analysis nothing further would be gained by such a study.

The data given in the tables have been plotted and the graphs serve as a convenient basis for discussion of the results.

(*a*) *Secondary Creep.*—A previous work [6] presented the effects of continuous-filament yarn geometry on the non-recoverable extension (secondary creep) following mechanical conditioning. It was shown that at equal conditioning loads the higher the yarn twist the greater the permanent set, and that this effect was the result of higher filament stresses being produced in a high-twist yarn.

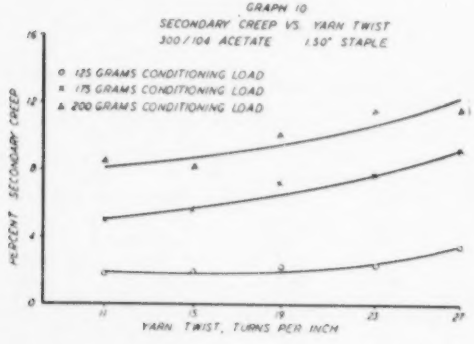
When staple-fiber yarns are considered, the effects of fiber slippage become of considerable importance. In the preceding sections on stress-strain properties to rupture it was indicated that the amount of slippage was greater for 1½-in. staple yarns than for 2½-in. staple yarns, and that for both yarns the effect of the high helix angles produced by twist increases was sufficiently great to counteract any increased binding. It would then be expected that:

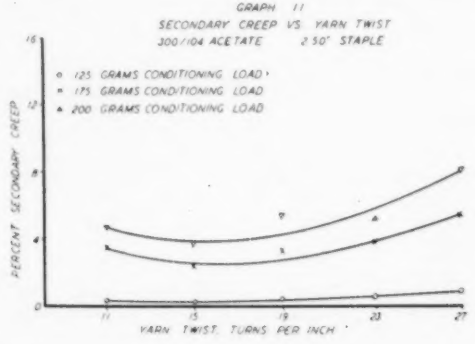
(1) For both 1½-in. and 2½-in. staple yarns, the higher the conditioning load the greater the secondary creep.

(2) At equal conditioning loads, the greater the yarn twist the greater the secondary creep.

(3) At equal conditioning loads and equal twists, the 1½-in. staple yarns would exhibit greater permanent set than the 2½-in. staple yarns.

In Graphs 10 and 11 are shown the effects of conditioning load on secondary creep for the 1½-in. and 2½-in. staple yarns, respectively. It can be seen from these graphs that, for both yarns, as the conditioning load increases the secondary creep

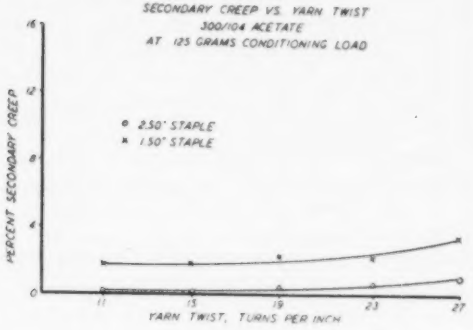




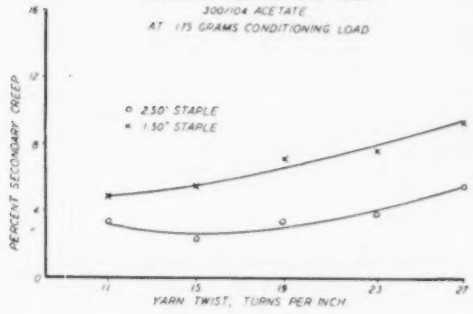
increases. This effect results from both higher inherent permanent set in the acetate fibers with increases in load and the increase in slippage to be expected with increases in the maximum tension.

There are two other points to be noted from Graphs 10 and 11:

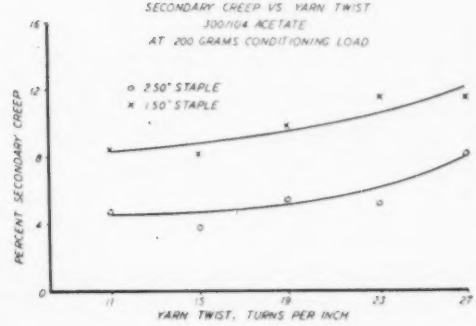
GRAPH 12
SECONDARY CREEP VS. YARN TWIST
300/104 ACETATE
AT 125 GRAMS CONDITIONING LOAD



GRAPH 13
SECONDARY CREEP VS. YARN TWIST
300/104 ACETATE
AT 175 GRAMS CONDITIONING LOAD



GRAPH 14
SECONDARY CREEP VS. YARN TWIST
300/104 ACETATE
AT 200 GRAMS CONDITIONING LOAD



(1) It would appear that the 2½-in. staple (Graph 11) exhibits a minimum in permanent set at about 15 t.p.i., while for the range of twists studied the 1½-in. staple does not show a minimum. This, if true, would not be in keeping with the commonly accepted belief that optimum twist is less for a long staple than for a short. However, it is more probable that the curves of Graph 11 would not exhibit this minimum if a greater number of tests had been made to define the average values, and that, for the range of twists studied, secondary creep would increase parabolically with load.

(2) It was shown in the study of continuous-filament yarns [6] that the increase in secondary creep, at a given twist, became less as the conditioning load increased. The data for staple yarns given in Graphs 10 and 11 do not indicate this trend. Apparently the effect of increase in fiber slippage with increase in load is masking the rate at which inherent secondary creep is being removed and no particular trend in the gross rate at which secondary creep is removed with load is evident.

Graphs 12, 13, and 14 illustrate the differences in secondary creep between the 1½-in. and the 2½-in. staple yarns at conditioning loads of 125, 175, and 200 g., respectively. It is to be noted that:

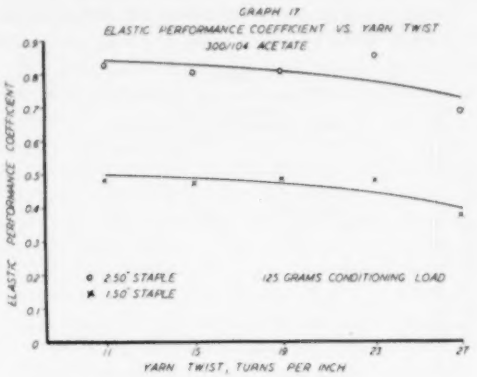
(1) In all cases, at equal conditioning loads and twists, the 1½-in. staple exhibits more permanent deformation than the 2½-in. staple. The curves for secondary creep *vs.* twist are parabolic and, comparing staple lengths, are essentially parallel to each other. Once again, lack of frictional cohesion has produced the difference between the 1½-in. and 2½-in. staple. On an absolute basis, the higher the load the greater the difference, but on a percentage basis, the difference apparently decreases with increase in load.

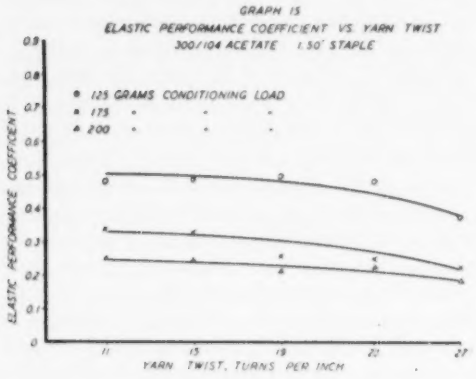
(2) Both yarns exhibit more secondary creep than do the continuous-filament yarns of equal twist. Secondary creep is manifested for the 12.0 and 24.0 t.p.i. continuous-filament yarns at about 190 and 180 g., respectively. As shown on Graph 12, both staple yarns exhibit secondary creep at loads as low as 125 g., whereas preliminary data indicated the 1½-in. staple to show permanent set at even 100 g.

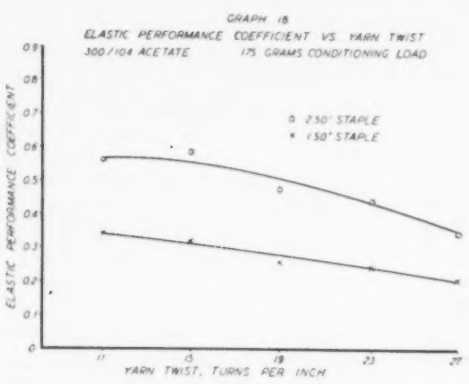
It should be noted that the maximum secondary creep capable of being removed from the continuous-filament yarns, approximately 20%–25%, far

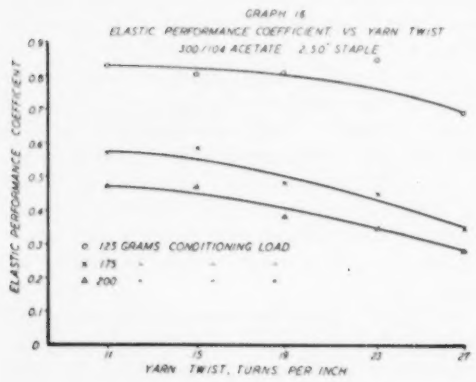
exceeds the amount which can be removed from either of the two staple yarns. However, this merely reflects the fact that the continuous-filament yarns are capable of being stressed at a sufficiently high load that nearly all of the inherent permanent set possessed by the material is removed. The staple-fiber yarns, on the other hand, exhibit, because of fiber slippage, higher gross secondary creep at the same load than the continuous-filament yarn, but the high inherent secondary creep of the fibers never makes itself evident, since rupture resulting from fiber slippage occurs at a sufficiently low load to preclude the majority of fibers being stressed to their ultimate capacity.

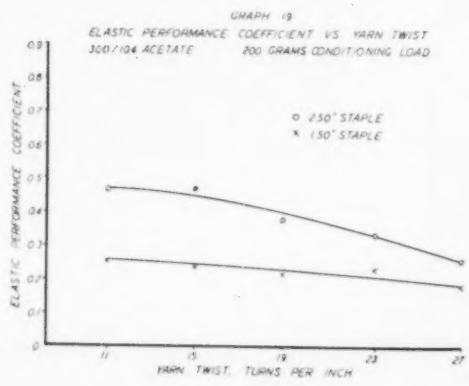
(*b*) *Elastic Performance Coefficient* (*E.P.C.*) [7].—It has already been established for continuous-filament yarns [6] that the higher the yarn twist the lower the elastic performance coefficient. Considerations of the effects of fiber slippage serve to explain variations in this property for yarns of different staple length.











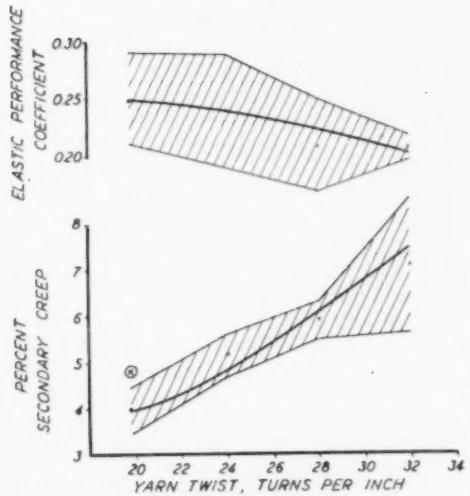
Graphs 15 and 16 plot the elastic performance coefficients at various conditioning loads for the 1½-in. and 2½-in. staple yarns, respectively. The following will be observed:

(1) For either staple length and at any conditioning load, the higher the yarn twist the lower the E.P.C. As was the case for the continuous-filament yarns, the E.P.C. decreases parabolically with twist. This, of course, would indicate that the effect of helix angle on stress is basically the same for staple-fiber yarns as for continuous-filament material.

(2) The higher the conditioning load the lower the E.P.C., indicating again that both inherent and geometrical effects are contributing to changes in the elastic performance coefficient.

The influence of yarn staple length on the E.P.C. is illustrated on Graphs 17, 18, and 19, for conditioning loads of 125, 175, and 200 g., respectively. The results are entirely in accord with what would be anticipated on the basis of the preceding discussion. At any conditioning load, the E.P.C. of the 2½-in. staple yarn exceeds that of the 1½-in. staple, and the corresponding continuous-filament data are higher still [6]. In all cases, increases in twist produce decreases in the E.P.C. in a manner similar to that exhibited by the continuous-filament material. The curves are essentially parabolic, with a tendency for the values of the 2½-in. staple to approach those of the 1½-in. staple at high twists.

GRAPH 20
REPEATED STRESS CHARACTERISTICS OF COTTON YARNS (13.8's)
500 GRAMS CONDITIONING LOAD



F. Elastic Characteristics of Cotton Yarns

The influence of yarn geometry on the elastic properties of staple acetate yarns having been explained, it is of interest to determine whether similar effects and explanations thereof can be noted for other materials. The same cotton yarns whose rupture properties have already been discussed were subjected to repeated-stress action. The results obtained are plotted on Graph 20.

The curves of Graph 20 represent the properties as determined at a conditioning load of 500 g. In addition, for the lowest-twist yarn only (19.8 t.p.i.) secondary creep at a conditioning load of 650 g. is plotted as the point ⊗.

From Graph 20 (bottom) it is seen that increase in conditioning load on a 19.8 t.p.i. yarn has resulted in an increase in secondary creep. Hence, it is concluded that for cotton yarns of this type secondary creep increases with fiber tension. Therefore, since stress distribution shows that higher-twist yarns are subjected to increasing fiber tensions at a given yarn load, it is apparent that the curve of secondary creep *vs.* yarn twist indicates that the permanent set increases with increase in twist. The curve of Graph 20 (bottom) indicates the increase to be parabolic—*i.e.*, of the same type as that observed for staple acetate.

On Graph 20 (top) are shown the values of the E.P.C. for these same cotton yarns. Here, also, the effects of yarn twist at a given conditioning load arise from the stress distribution-twist relationships. The shape of the curve is the same as that for staple and continuous-filament acetate—namely, parabolic.

G. Summary of Influence of Yarn Geometry on Yarn Elastic Properties

The elastic properties of yarns with different inherent fiber properties and different geometry have been investigated through consideration of the stress-strain diagrams for both one-time and repeated loading, with the following results:

(1) Independent of the staple length, including continuous filament, increases in yarn twist produce

similar trends (parabolic) in elastic properties—*viz.*, decrease in E.P.C. and increase in secondary creep.

(2) Independent of twist, the longer the staple length the better the elastic characteristics—*i.e.*, the higher the E.P.C. and the less the secondary creep.

(3) The elastic characteristics become poorer at higher conditioning loads.

(4) Within the range of staple-yarn twists studied, the elastic properties of staple yarns are similar in trend to, although different in magnitude from, the continuous-filament yarns.

(5) Helix angle effects similar to those observed for the continuous-filament yarns apply in principal to the staple-fiber yarn, and, when combined with slippage effects, serve as the basis of explanation of staple-yarn properties.

(6) It is indicated that for both staple acetate and cotton yarns the same dependence of rupture properties and repeated-stress properties upon yarn geometry and stress-strain curves exists as for continuous-filament yarns. Whereas to predict rupture properties of filamentous yarns it is necessary only to predetermine the fiber (or zero-twist yarn) stress-strain curve, to predict those of staple yarns requires the predetermination of the stress-strain curve for a yarn whose twist exceeds the optimum.

(7) It appears that increases in twist beyond the optimum do not add further cohesion to a staple yarn, and hence all changes in strength and elastic performance with twist beyond the optimum twist arise wholly from changes in fiber inclination as it affects stress distribution.

Acknowledgment

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Mechanics of Elastic Performance of Textile Materials

Part V: A Study of the Factors Affecting the Drape of Fabrics—The Development of a Drape Meter

Chauncey C. Chu, Clinton L. Cummings, and Newton A. Teixeira

Fabric Research Laboratories, Inc., Boston, Massachusetts

Introduction

"Drape" and "drapability" are terms for that property of textile materials which allows a fabric to orient itself into graceful folds or pleats when acted upon by force of gravity. Hence, a fabric is said to have good draping qualities when the configuration is pleasing to the eye. Obviously, then, the word "drape" is a qualitative term. The textile industry realizes the importance of understanding the phenomenon of drape and is anxious to be able to measure it quantitatively.

Numerous "drape tests" have been reported in the literature, but none have presented any correlation between the data obtained and subjective evaluations. This is largely because of the failure to realize that drape may not be determined conclusively by those tests which involve two-dimensional distortions of the fabric samples. (These tests are typified by the "Drapeometer" [2] and "loop" tests of various shapes [1].) Present-day two-dimensional distortion tests are incapable of differentiating between drape and paperiness—*i.e.*, it is possible to select a piece of paper and a piece of fabric both of which have the same bending properties, yet it is doubtful that the paper will drape as well as the cloth. Children's party costumes are often made of crepe or tissue paper; however, regardless of how flexible the paper may be, it does not have the same appearance as cloth—it is seldom graceful. In other words, the paper does not drape!

It is obvious that a test instrument which is capable of distorting the sample in all three dimensions is necessary if drape is to be evaluated quantitatively. The drapability of yard goods is usually displayed in store windows by draping the fabrics over circular pedestals. This simulates service conditions, in which a cape, for example, is draped over the shoulders or a skirt around the hips of the wearer. The F.R.L. Drapemeter was designed on a similar principle.

The original F.R.L. Drapemeter is an optical instrument. It is shown diagrammatically in Figure 1. The sample holder consists of two flat plates, circular in shape, mounted on a shaft coming through the base of the tester. The circular sample is sandwiched between the plates, and the shaft is raised until the overhanging portions of the sample no longer touch the base. The image of this draped pattern is cast onto a sheet of ground glass by means of a lens system. This pattern is then traced on a thin piece of paper.

Figures 2 and 3 show typical drape diagrams traced from the ground-glass sheet. The smaller circle indicates the position and size of the supporting disc and the larger circle indicates the original size of the sample. The shape and size of this pattern are governed by the draping qualities of the sample tested. For convenience in comparing different samples, the term "drape coefficient" is used, which is defined as the percent of the annular-ring area covered by the draped sample. This area is indicated by the shaded portions of Figures 2 and 3.

Since the draped sample will form pleats, its circumference can no longer remain in only one plane. As a result, the traced image is not necessarily the true projected one. For example, if points *A* and *B* (Figure 1) on the circumference are the same distance from the axis but are at different elevations, then their respective projections on the

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ground-glass sheet would be A' and B'. A study was made to evaluate this error. Results show that for a difference in elevation of 1 in. the error for the image diameter is 8.5%, or a maximum error for the enclosed area of about 17%. Since this error is excessive, an improved model was designed and constructed.

The Improved F.R.L. Drapemeter

Working Principles

The problem of determining the projected area of a draped sample was solved as described below. The improved F.R.L. Drapemeter is diagrammed in Figure 4 and photographs are shown in Figure 5.

One of two synchronized turntables supports the draped sample and a standard circular chart is mounted on the other. A light beam from a small lamp is focused on a photocell, both elements being mounted in a movable unit. This optical system scans the draped sample and automatically and continuously positions itself at the edge of the fabric. The movements of the photocell are recorded on the chart by a pen which is mounted in a carriage which is mechanically connected to the scanning unit. Thus, when the turntables have performed one complete revolution, an accurate vertical projection of the draped sample is drawn on the circular chart.

Analysis of Instrument

Optical System.—The components used in the optical system are two photocells of the photovoltaic type, two lamps, a filament transformer, a potentiometer, and a collimating lens.

One photocell, P.E.$_c$, used as a comparison cell, is illuminated by a lamp which is connected to the filament transformer through a potentiometer. The scanning cell, P.E.$_s$, receives the light from a second lamp through a collimating lens. The brightness of the lamp in the comparison unit is adjusted until the light falling on the comparison cell is approximately equivalent to the light which falls on the scanning cell when the beam is cut in half by the edge of the sample. The outputs of the two cells are bucked against each other in a series connection, and a voltage equal to the algebraic difference between their voltages is applied to the input of an amplifier. When the illumination on both cells is equal, their combined output is zero. If the illumination on the scanning cell is increased or decreased as a result of the rotation of the irregular projection of the sample, the output will be either a positive or a negative voltage. This output, amplified by an electronic system containing a phase-sensitive circuit, controls one phase of a two-phase motor which positions the scanning unit so as to restore the electrical balance between the scanning cell and the comparison cell. Then, as the sample and chart revolve synchronously, the amplifier-and-motor combination moves the scanning device so as to keep the light on the P.E.$_s$ equal to that which will balance-out the output of the comparison cell, the illumination of which is fixed.

Mechanical Operation.—A synchronous motor, geared to 1 revolution per min., drives the chart table and, by means of sprocket gears and a roller chain, also turns the sample. Discs as large as 10 in. in diameter may be used to hold the sample, depending upon the sample characteristics, as de-

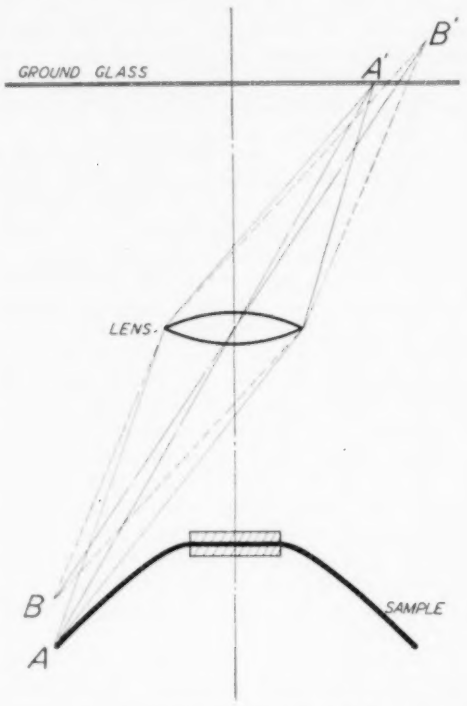


FIG. 1. *Schematic diagram of F.R.L. Optical Drapemeter.*

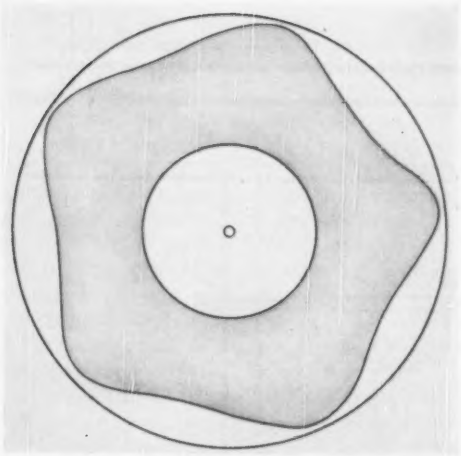


FIG. 2. *Typical drape diagram for sateen.*

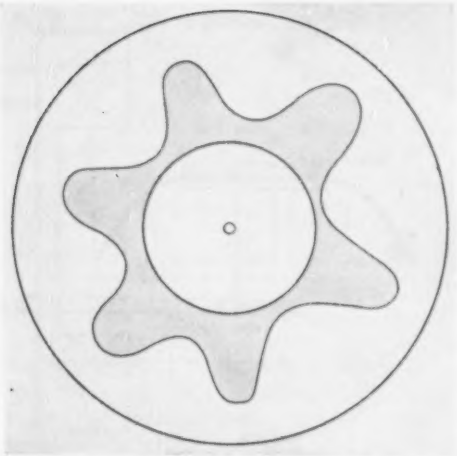


FIG. 3. *Typical drape diagram for acetate fabric, plain weave.*

scribed on page 547 of this report. In order to place the sample on the disc without distorting it, the shaft of the sample turntable may be slid down until the disc is flush with the cabinet. Once the sample is in place, the table is raised to its proper operating position, with the sample disc as close to the photocell as possible. This sliding shaft is also useful for raising and lowering the sample in order to work it to a stable equilibrium condition. This working process is more fully explained in a subsequent part of this report (page 543).

The turntable which holds the chart is 12 in. in diameter and has a small, vertically projecting knob which is positioned about ½ in. off-center in order to keep the paper from slipping as the table revolves. Standard circular charts may be used.

A two-phase motor, driven by the amplifier output and connected to a wire-and-pulley system, moves the scanning unit along a straight line between turntable centers. The direction of rotation of the motor is such that the scanner is moved until the edge of the fabric cuts the light beam and the light reaching the moving cell is equal to that incident upon the fixed cell. Connected to the scanner by two horizontal rods is a pen carriage which holds the pen on the line between turntable centers. Thus, the radial movements of the scanning unit at the rotating sample are exactly duplicated by the radial motion of the pen on the rotating chart. Table rotation is started by manually depressing the repeat button. The discs are automatically stopped by a limit switch after each complete revolution.

Amplifier Unit.—This unit converts the direct voltage output of the photocell to alternating voltage and amplifies this voltage in order to operate a phase-sensitive circuit controlling one phase of the two-phase motor which is used to position the scanning unit. The amplifier consists of the following parts: an interrupter or chopper which converts the direct voltage to alternating voltage; an alternating-current amplifier; and a phase-sensitive output circuit which is connected to one phase of the motor. The amplifier and motor make up a matched unit.

Operating Instructions

Sample Preparation.—The samples used on this instrument are 10 in. in diameter, although samples as large as 12 in. in diameter may be accommodated. The circle may be drawn on the fabric by means of a compass, with appropriate markings to locate the center. The samples with a ¼-in. hole in the center are carefully cut out with scissors, care being taken to avoid distortion or creasing of the fabric. They are conditioned for 24 hrs. before testing in order to relieve any localized stresses caused by handling during preparation.

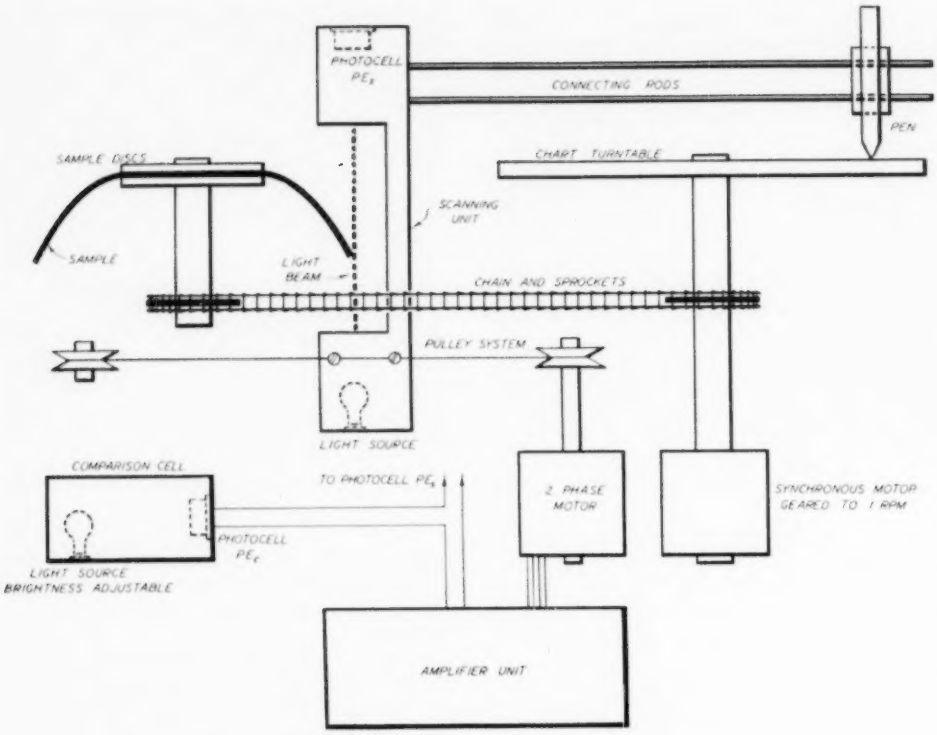


FIG. 4. *Schematic diagram of the improved F.R.L. Drapemeter.*

Calibrating the Drapemeter.—The instrument may be calibrated according to the following procedure:

1. Turn on main switch; allow about 10 min. for the machine to warm up.

2. Place a blank chart on the chart table. Using the sample disc (either 4 in. or 5 in.) as a guide, trace a circle on the chart.

3. Raise the hood, remove the sample disc from the chart table and place it on the spindle; replace the hood and turn on the photocell switch.*

4. Set the planimeter wheel on the circle which was previously traced on the chart. This is done by sliding the pen carriage along the connecting bars.

5. Press the repeat button to begin rotation. After one complete revolution, read the area from the planimeter dial.

6. Compare this value with the actual area of the sample disc. (See Table I.)

7. Adjust the position of the pen carriage and repeat steps 5 and 6 until the area obtained is within 0.10 sq. in. of the actual value.

* The photocell switch must be turned off when the hood is raised; otherwise, the unbalance of lighting will cause the photocell to move beyond its normal limits.

TABLE I. AREA OF CIRCLES

	$\beta^* = 0.4$	$\beta^* = 0.5$
Diameter of sample disc (d), in.	4	5
Area of sample disc (A_d), sq. in.	12.57	19.64
Diameter of sample (D), in.	10	10
Area of sample (A_D), sq. in.	78.54	78.54
Area of the annular ring ($A_D - A_d$), sq. in.	65.97	58.90

$$^*\beta = \frac{\text{Diameter of sample disc}}{\text{Diameter of sample}} = \frac{d}{D}$$

Test Procedure.—

1. Depress sample disc and its spindle so that the top surface of the sample disc is flush with the base of the tester.

2. Transfer the prepared sample onto a slotted plate which is slightly larger than the sample itself, care being taken to minimize flexing or distortion of the sample. The plate, together with the sample, is placed in the tester above the sample disc, and the plate is then carefully slid out from under the sample. The plate facilitates mounting the sample without distortion.

3. Place a weighted disc which is the same size as the sample disc over the sample so that the center portion of the sample will be held tight.

4. Raise the sample by pulling on the spindle until the overhanging portions of the sample clear the base of the tester. Lower it to its original position and repeat this process ten times. This is done to "mechanically condition" the sample. (Note: a number of tests were done without using this procedure; the results are noticeably different. See data in Table II and discussion which follows.)

5. After "conditioning," raise the spindle until the top of the weighted disc is just below the photocell, and then begin the test by turning on the photocell switch and pressing the repeat button.

6. The area under the draped sample is determined by using the integrator mechanism. (Description of the integrator is given in this report on page 544.) The area may be read from the integrator dial after one complete revolution of the turntables.

7. Replace the integrator with the pen, and rotate the sample again to make a permanent chart.

TABLE II. EFFECT OF "MECHANICAL CONDITIONING" ON DRAPE COEFFICIENT, *F*

	Fabrics						
	A	B	C	D	E	F	G
Test 1 (unconditioned)							
% *F**	79.2	82.7	72.0	78.7	72.2	74.4	67.7
Standard deviation	8.3	2.4	1.9	6.1	4.8	4.5	3.3
Test 2 (conditioned)							
% *F**	70.4	79.6	66.3	60.7	64.1	62.5	61.3
Standard deviation	5.5	3.0	3.2	5.1	2.6	2.5	3.4

* For these fabrics, the area of the annular ring is:
$\pi(r_o^2 - r_i^2) = \pi(25-4) = 66$ sq. in.

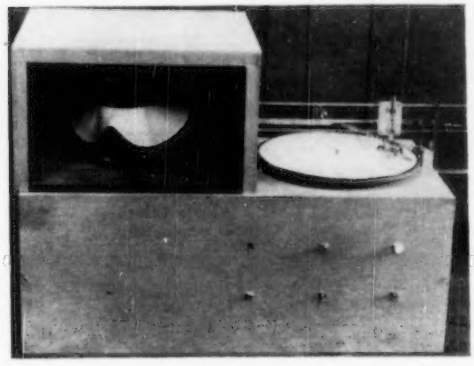
It is advisable to draw a set of reference circles on the same chart. The reference circles are those drawn using the sample disc and the 10-in. disc. Even though the area measurement and the drape diagram are not made during the same cycle, tests have shown that the projected area remains virtually unchanged for 2 or even 3 cycles. In future models it will be possible to make the area measurement and the drape diagram simultaneously.

Calculations.—Analysis of test data, at present, involves only the drape coefficient, *F*, which is defined as the fraction of the area of the annular ring covered by the projection of the draped sample. This, in effect, is analogous to the circularity coefficient which is used in textile microscopy.

$$F = \frac{\text{Area under the draped sample}}{\text{Area of the annular ring}},$$

where the area of the annular ring is the difference between the area of the circular sample and that of the sample disc.

The effect of "mechanically conditioning" the sample can best be shown by the test data given in Table II. Test 1 was performed without the con-



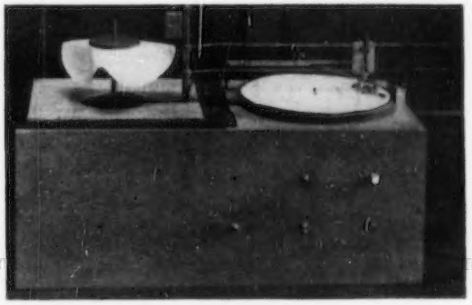


FIG. 5. *F.R.L. Drapemeter.* Left—*With hood.* Right—*Hood removed.*

ditioning process, and Test 2 with conditioning. It can be seen that the values of the drape coefficient, F, for Test 2 fabrics are smaller than those for Test 1 fabrics, and so are the standard deviations in most cases.

Integrator Unit.—Since the evaluation of drape by using this instrument depends upon the ratio of the projected area to the flat area of the sample, some method of determining the projected area must be used. The chart may be planimetered in the customary fashion, but this method is time-consuming and its precision is limited by operating errors. (See Figures 6 and 6A.)

For this reason, an integrator unit was developed which could be mounted in place of the pen and used to give the area directly by making one or more rotations of the sample and chart.

Nomenclature:

P = location of light beam on sample
P' = point of tangency of integrator wheel
C = length of connecting bar from Q (pivot on slider) to P' (axis of integrator wheel is along C)
D_p = diameter of planimeter wheel
ω = angular velocity of planimeter wheel
v_w = tangential velocity of planimeter wheel
ω_T = angular velocity of chart table
v_T = tangential velocity of chart table at P'
v_p = component of v_T perpendicular to axis of planimeter wheel
r = distance of P' or P from the center of their respective turntables
θ = angle between the connecting bar C and the supporting bar BB'

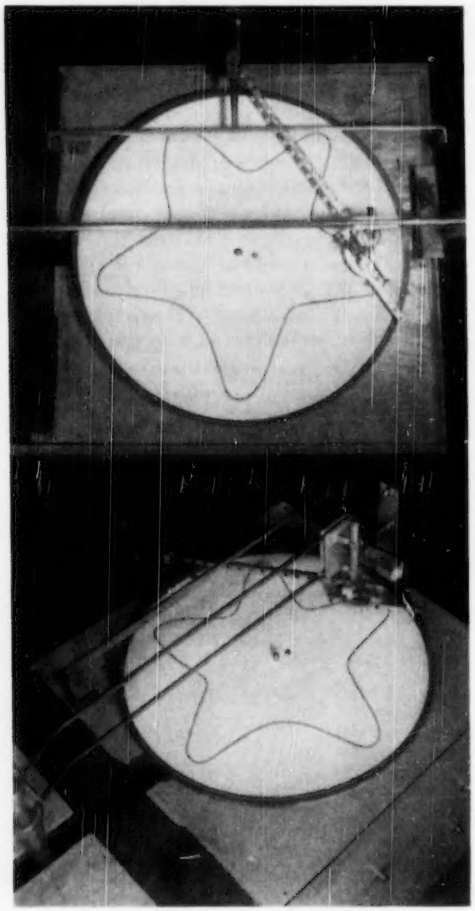


FIG. 6. *Integrator.*

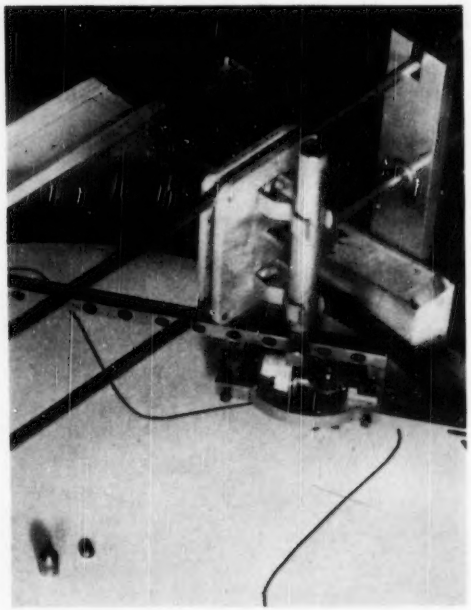


FIG. 6A. *Integrator (closeup of planimeter).*

If there is zero slip between the planimeter wheel and the chart paper, then

$$v_p = v_T \sin \theta. \tag{1}$$

Since

$$v_w = \frac{D_p}{2}\omega, \tag{2}$$

and

$$v_T = r\omega_T, \tag{3}$$

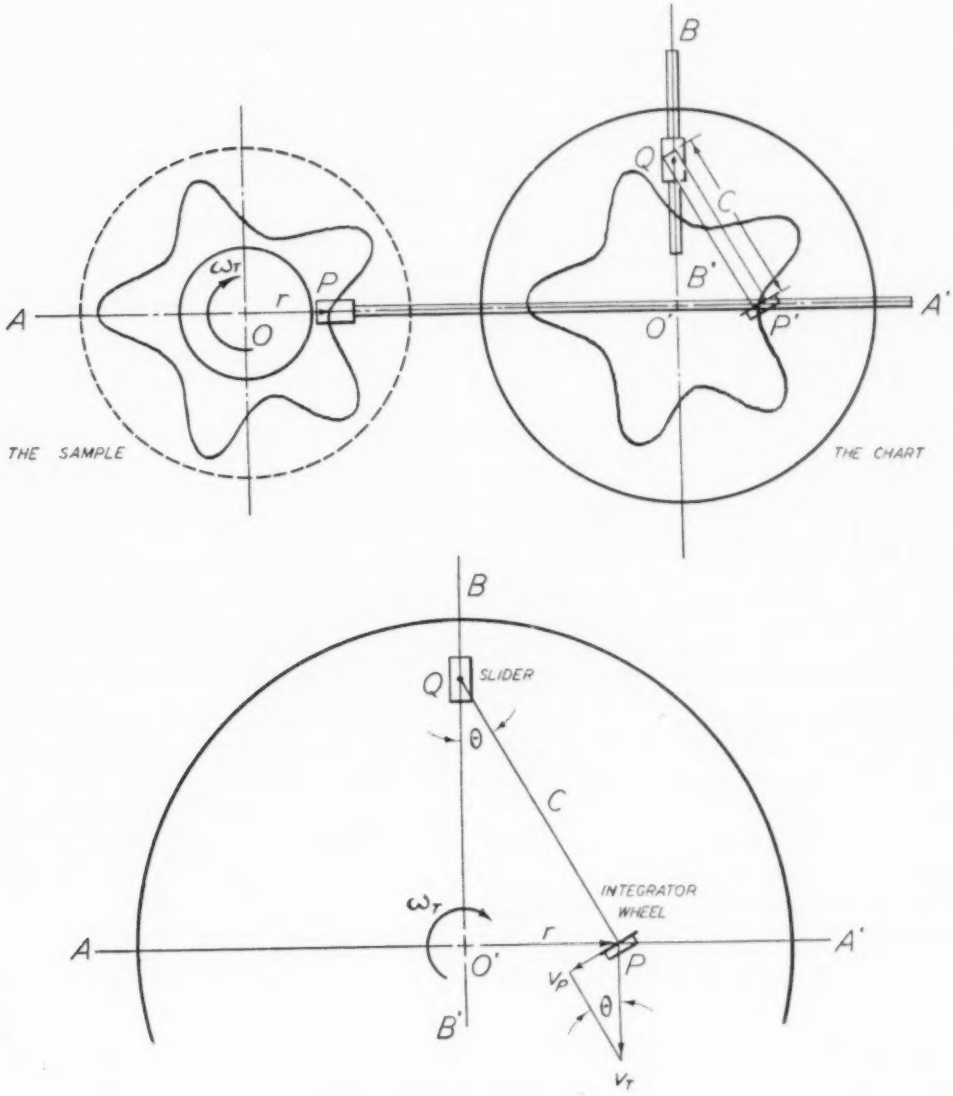


FIG. 7. *Schematic drawing of integrator.*

(Carriage of integrator wheel (bar C) is fastened to moving bar (along AA') by a pin joint just above P'. Supporting bar BB' is perpendicular to connecting rods AA' and in line with O', the center of chart table).

and at the point of tangency between the planimeter wheel and the chart, P',

$$v_w = v_p, \tag{4}$$

then from equations (1), (2), (3), and (4)

$$\omega = \frac{2v_w}{D_p} = \frac{2v_T}{D_p}\sin\theta = \frac{2r\omega_T}{D_p}\sin\theta. \tag{5}$$

From the diagram (Figure 7)

$$\sin\theta = \frac{r}{C}. \tag{6}$$

Substituting equation (6) into equation (5),

$$\omega = \frac{2r\omega_T}{D_p}\frac{r}{C} = \frac{2\omega_T}{CD_p}r^2. \tag{7}$$

But

$$\omega_T = \frac{d\theta}{dt} = \text{constant}. \tag{8}$$

Therefore

$$\omega = \frac{2r^2}{CD_p}\left(\frac{d\theta}{dt}\right). \tag{9}$$

Let the total angle through which the wheel turns be φ:

$$\varphi = \int \omega dt = \frac{2}{CD_p}\int r^2\frac{d\theta}{dt}dt$$

$$= \frac{2}{CD_p}\int_0^{2\pi} r^2 d\theta = \frac{4}{CD_p}\int_0^{2\pi}\frac{r^2}{2}d\theta. \tag{10}$$

If the pattern is a circle, then r is constant and

$$\varphi = \frac{4}{CD_p}\left(\frac{r^2}{2}2\pi\right) = \frac{4}{CD_p}\left(\pi r^2\right)$$

$$= \frac{4}{CD_p}(\text{area of circle}). \tag{11}$$

Let

$$\varphi = 2\pi N, \tag{12}$$

where N is the number of revolutions of the planimeter wheel. Substituting equation (12) into equation (10),

$$N = \frac{2}{\pi CD_p}\int_0^{2\pi}\frac{r^2}{2}d\theta, \tag{13}$$

and $\frac{2}{\pi CD_p}$ is the number of revolutions per unit area, or $N = \frac{2}{\pi CD_p}(\text{area})$ since $\int_0^{2\pi}\frac{r^2}{2}d\theta$ is equal to the area for any pattern.

For proper operation of the slider, θ should not exceed about 50° and, therefore, C should be sufficiently greater than the radius of the turntable that $\sin\theta = \frac{r}{C} = 0.6$. Maximum r as limited by maximum sample size = R = 5 in. C should then be approximately $\frac{5}{0.6}$ = 8.3 in. The diameter of the wheel available from a standard planimeter was $D_p = 0.77\text{Z}$. If $\frac{2}{\pi CD_p}$ should be about 0.1 rev./unit area for the desired precision, then

$$\frac{2}{\pi CD_p} = \frac{2}{\pi(0.772)C} = 0.1$$

and

$$C = \frac{20}{\pi(0.772)} = \frac{20}{2.425} = 8.247 \text{ in.}$$

Then

$$N = 0.1\,(\text{area}) = 0.1\int_0^{2\pi}\frac{r^2}{2}d\theta,$$

and A (area) = 10 N, where N may be read off the planimeter wheel up to 10 revolutions and to two decimal places. The maximum reading of the integrator is 10.00 revolutions, or 100.00 sq. in.

Advantages and Limitations

Variety of fabrics which may be tested.

Autographic diagram which may be kept as a record. Several diagrams may be made on the same chart for various time intervals in order to show relaxation of fabric.

Mechanically computed area is traced more precisely than can be done even by skilled operators using a hand planimeter.

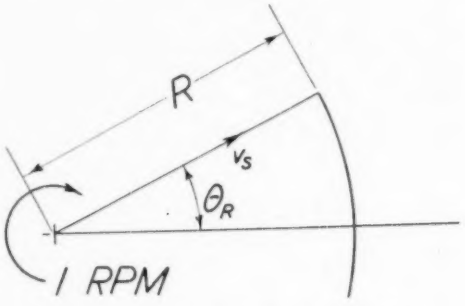


FIG. 8. *Minimum angle of resolution.*

Ease and simplicity of operation. No experience is required in evaluation.

Little time is required per test. One revolution in 1 min. is required to produce the diagram, and fabrics may be mounted in about the same amount of time.

Accuracy and Precision.—Since this is a null operating system, the accuracy of the diagram is equal to the precision of calibration, which in turn depends only upon the width of the light beam, which may be kept to a minimum by focusing and by the use of a pinpoint light source. As shown below, the precision and accuracy of the integrator are greater than the precision with which a sample may be cut.

Reproducibility.—Two samples were cut from cardboard according to an actual drape diagram and were used in place of fabric samples. Table III shows the results of these tests.

Minimum Angle Resolvable.—In the present developmental model, the minimum angle of resolution is established as that angle which will barely allow the scanning unit to move from a small radius to a large radius without the sample striking the photocell support. By effecting a minor change in the photocell carriage, the minimum angle may be reduced to that angle which is determined by the ratio of the maximum speed of the scanner to the speed of the turntable.

If the velocity of the scanner is equal to v_s (in in. per min.) and the turntable speed is one revolution per min., then (Figure 8) $\theta_R = \dfrac{(1 \text{ r.p.m.})360}{v_s/R}$, the maximum R is 5 in., and

$$\theta_{R\,\min} = \frac{360}{v_s/R} = \frac{360}{v_s/5} = \frac{(360)5}{v_s} = \frac{1800}{v_s}.$$

v_s is equal to about 5 in. per sec. but may be varied slightly by adjusting the damping. Then

$$\theta_{R\,\min} = \frac{1800}{5 \times 60} = 6°.$$

In actual practice, any drape sample which might fold this sharply would also tend to curl under, thus requiring a larger mounting disc. This angle of resolution, therefore, is more than adequate for any practical work.

Translucency of Fabrics.—This factor becomes important only when the translucency varies across the fabric or when the fabric does not sufficiently alter the light beam. Even for sheer white nylon the machine seems to perform satisfactorily.

TABLE III. REPRODUCIBILITY OF F.R.L. DRAPEMETER RESULTS

Test No.	Area, sq. in. Sample 1	Sample 2
1	28.92	50.04
2	28.82	49.96
3	28.96	50.08
4	28.89	50.27
5	28.96	50.03
6	28.85	50.06
7	28.97	50.00
8	28.89	49.99
9	29.00	49.75
10	28.99	49.94
Average	28.925	50.012
Standard deviation	0.061	0.041
Coefficient of variation	0.32%	0.08%

Accuracy of Calibration and Drift.—Using a 4-in. disc for calibration, the following results were obtained:

Average area	12.533 sq. in.
Standard deviation	0.048 sq. in.
Coefficient of variation	0.38%

Radius of disc = 2 ± 0.002 in.

Area of disc = 12.566 ± 0.025 sq. in.

$$\text{Error} = \frac{0.025}{12.566} = 0.2\%$$

The above discussion pertains to the present developmental model only; the means are already known for changing the design in order to remove most of the limitations mentioned here, and also for making the machine more versatile and more sensitive for use as an area-measuring device in its general application.

Experimental Procedure for Strip Bending-Flexibility Test

Inasmuch as drape must be related in part to the bending properties of fabrics, a small percentage of time has been spent on simple strip bending tests. These tests were carried out simultaneously with the drape tests. The following is a description of the test procedure.

Samples are accurately cut from the fabric to be tested with a dink or a razor blade to 6 in. by 1 in. Other tests have shown no difference in results when samples are cut by different means. The

edges of the sample are made to follow the lengthwise threads as closely as possible. It is desirable that samples be handled as little as possible, because bending and folding alter the stiffness and produce lines of crease or weakness that make the results meaningless.

The specimen is mounted in the tester as illustrated in Figure 9. This tester is a much simplified version of Peirce's Flexometer [1]. A steel ruler covers the specimen to be tested, with the end of the ruler matching the end of the specimen. A weight is used to hold the sample down to the platform. The ruler, together with the sample, is gradually extended over the platform. Care is taken that there is no relative motion between the ruler and the sample. When the overhanging end touches the 43° line, measurement is taken from the ruler to see how far it has protruded beyond the edge of the platform. The bending length, c, is taken as one-half of this value. This relationship was derived as follows:

Peirce defined the bending length as:

$$c = L\left(\frac{\cos 0.5\theta}{8 \tan \theta}\right)^{\frac{1}{3}},$$

where L = length of overhang and θ = chord angle of the deflection curve.

If we set

$$c = \frac{L}{2},$$

then

$$\left(\frac{\cos 0.5\theta}{8 \tan \theta}\right)^{\frac{1}{3}} = 1/2,$$

or

$$\tan \theta = \cos 0.5\theta.$$

Solving for θ,

$$\theta = 43° \text{ (approximately)}.$$

Many fabrics tend to curl and twist when cut into small specimens, and this affects the reproducibility and the physical meaning of the test results. In order to remedy this, readings are taken for both sides of the fabric, and then the test is repeated on the same specimen with the ends reversed, so that the two values of the bending length for any one specimen are obtained from four readings of overhanging length.

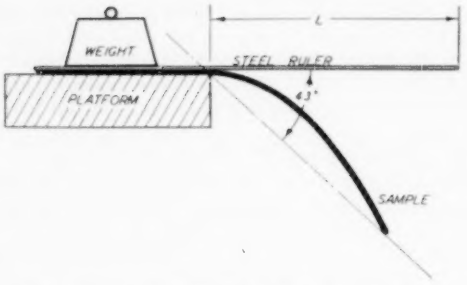


FIG. 9. *Schematic diagram of strip bending tester.*

The number of samples necessary to give a representative value for the bending length depends upon the regularity of the results and the degree of accuracy demanded. Five in each direction, warp and filling, is a reasonable number.

Acknowledgment

Gratitude is expressed to Dr. W. J. Hamburger, Dr. M. M. Platt, and Mr. W. J. Klein for their constructive suggestions relevant to the Drapemeter and to this paper.

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2. Schwarz, E. R., and Winn, L. J., Technical Evaluation of Textile Finishing Treatments, *Am. Dyestuff Reptr.* **30**, 226 (1941).

(*Manuscript received May 16, 1950.*)

Ultrasonic Disintegration of Cellulose Fibers Before and After Acid Hydrolysis*

Frederick F. Morehead†

THE EFFECT of ultrasonic vibrations on both native and regenerated cellulose fibers is to break them down into thin, almost electron optically transparent "fibrils," the length and width of which depend upon the type of fiber. However, if the fiber is subjected first to acid hydrolysis followed by ultrasonic vibration, then "particles" instead of fibrils are obtained. The size and shape of these hydrolyzed cellulose particles are of two types, depending upon whether they originate from native or from regenerated fibers. It is the purpose of the present paper to show that the particle dimensions, which can be observed in the electron microscope, are in good agreement with the viscosity data and that they are apparently related to the crystalline and amorphous structure of the original fiber.

Experimental Procedure

Successful direct examination of cellulose in the electron microscope is dependent upon some means of disintegrating the cellulose sample to dimensions that are of the requisite fineness or thinness to allow electron penetration without any artifacts resulting from the heating effects of electron absorption. Such disintegration may be accomplished either mechanically [1, 5, 7, 11] or by the employment of ultrasonic vibrations [13]. Not only does the latter offer the advantage of easier control of heating effects, as the oil bath of the ultrasonerator may be cooled, but also the cellulose samples so treated are much less subject to bacterial attack because of the sterilizing action of the ultrasonic waves. Keeping the sample in the same test tube in which it was disintegrated aids in preserving it from contaminating growths.

Preparation of the Sample for Electron-Microscopic Examination

The following procedure was used for the preparation of samples of cellulose for ultrasonic treatment for examination in the electron microscope: 5–150 mg. of cellulose, fluffed into fibrous form and, in the case of long fibers, cut into short lengths (1–2 mm.) was placed in a 30 × 150-mm. test tube containing 25 ml. of distilled water and the test tube was placed in the center of cavitation in the oil bath of the Crystolab "Ultrasonerator," Model SL520. The frequency used was 700 KC and the time of treatment was 20 min. Heating effects were minimized by cooling the oil bath with circulating ice water. Since not all of the fibers were completely broken up by this length of treatment, only the liquid above the mass of fibers was used for the final examination.

Two methods of preparing the material for the electron microscope were used: (1) evaporation of the sample on Formavar-coated screens and (2) evaporation on a glass microscope slide, followed by metal shadowing [12] and subsequent stripping of the metal replica. The first method is a little more convenient and allows the use of uranium metal and its thinner layer of shadowing material (due to its high atomic number), but it has the disadvantage that the structure of the supporting film is shown in the background. The "atomic replicas" prepared with palladium or platinum-palladium [12] have the advantage of a cleaner background, but they are more difficult to prepare. For placing the small drops of the liquid on the screens a platinum wire loop is convenient. If it is desired to keep the particles as well dispersed as possible, spraying [4] a film of the treated sample onto a glass surface with an atomizer is satisfactory. Metal "shadowing" [12] may be used advantageously to render more details visible.

* This paper was presented in part at the 1948 annual meeting of the Electron Microscope Society of America, Toronto, Canada, September, 1948.

† Chemical Research Department, American Viscose Corporation, Marcus Hook, Pa.

TABLE I

Fiber	Crystallite size	Orientation	Fibrils
Ramie	Large	Good	Very long
Rayons	Small	Good to poor	Long and short
Fortisan	Medium	Very good	Very long

The usual shadowing angle employed in this work was 5–1. Shadowing not only enhances contrast but also allows the measurement of the height (thickness) of the sample by means of the metal shadow.

Hydrolysis of Sample

Cellulose was added to boiling 2.5 *N* HCl and the flask was heated at the boil for exactly 15 min.; the residue was collected on a sintered glass filter and washed acid-free [3]. The temperature of the boiling HCl was carefully controlled by using a Glas-Col heating unit around the flask, and controlling this unit by means of a Variac and ammeter in order that the temperature could be kept at 105°C (± 0.50°) during the heating.

After it was washed acid-free and dried, 5–10 mg. of the hydrolyzed cellulose was placed in 25 ml. of distilled water and prepared for the electron microscope by treatment in the ultrasonerator and by shadowing, as was done in the case of the untreated cellulose. Owing to the much more complete breakdown of the hydrolyzed sample, it may be necessary to further dilute the sample before evaporating or spraying it onto slides or screens.

TABLE II

Time in boiling 2.5*N* HCl (min.)	D.P.	Length of crystallite Calculated*	Observed (Å.)
5	305	1,570	1,480
10	300	1,545	1,540
15	297	1,530	1,495
30	278	1,432	1,430
60	272	1,401	1,500

* D.P. (degree of polymerization) multiplied by factor of 5.15, the length of the glucose unit in Ångström units.

Results

Behavior of Untreated Cellulose Disintegrated by Ultrasonic Vibrations

All fibers that have been investigated to date have tended to break down into very fine fibrils. A typical example of this behavior is shown in Figure 1, which is an electron micrograph of wood-pulp fibers. No very definite pattern of fibril sizes or behavior

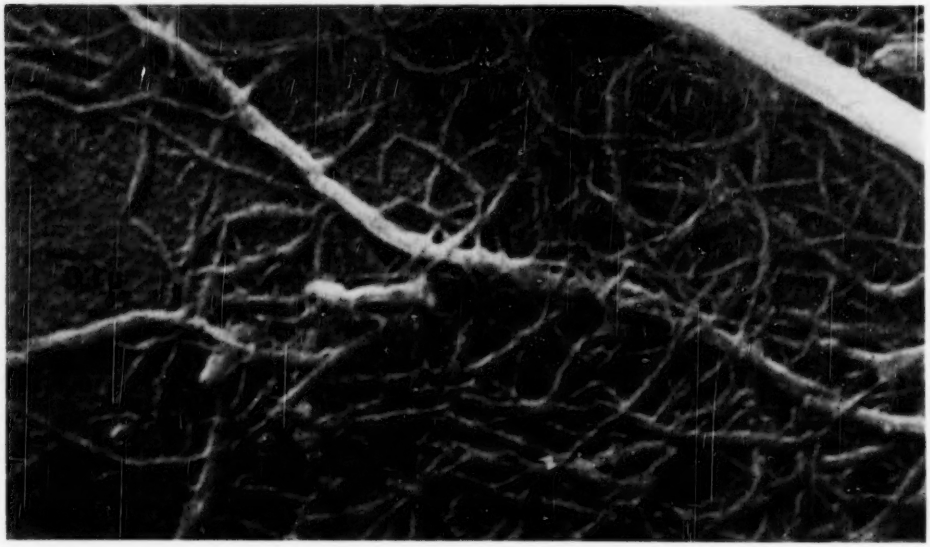

FIG. 1. *Electron micrograph of wood pulp disintegrated by ultrasonic vibrations—uranium-shadowed, 5–1 shadowing angle. Magnification 75,000×.*

TABLE III*

Fiber	D.P.	Observed crystallite length Min.	Max.	Av.	Cellulose chain length from D.P.	Crystallite thickness	Crystallite width	No. of cellulose chains
Cotton	280	910	2,080	1,460	1,442	50	64	113
Wood	297	1,200	3,300	1,450	1,530	37	45	63
Ramie	251	1,120	1,400	1,200	1,293	35	40	53
Fortisan	65			334	335	27	50	52
Rayon	50–60			240	254–309	23	50	45

* Dimensions of the crystallite are given in Ångström units.

has been observed except that the more highly oriented fibers tend to split up with the greatest ease [1, 5, 8, 11].

Table I summarizes the results obtained with the untreated cellulose.

Effect of Hydrolysis Plus Ultrasonic Disintegration on Samples Prepared from Native and Regenerated Cellulose

A study was made of the effect of time of heating in 2.5*N* HCl on the crystallite length of a sample of wood pulp as observed in the electron microscope. The results are given in Table II.

These results indicate the rapidity with which a reasonably constant value is obtained for both the leveling-off D.P. and the crystallite length and how these values are maintained for some time after the standard 15-min. time of treatment.

Figure 2 is an electron micrograph of the same wood pulp as that shown in Figure 1 after it had been hydrolyzed for 15 min. before disintegration. Many of the "particles" are obviously aggregates, which fact was taken into account in the measurements.

Table III gives the results of measurements on the crystallites observed after the acid hydrolysis of a number of native and regenerated celluloses. (Values were obtained for a number of different preparations of each kind of fiber.) Width was measured directly and thickness (height) was calculated from the cast shadow.

FIG. 2. *Electron micrograph of wood pulp hydrolyzed to a L.D.P. of 297, disintegrated by ultrasonic vibrations—palladium-shadowed, 5–1 shadowing angle. Magnification 75,000 ×.*

Since the volume of the crystallite may be determined from the observed dimensions, the calculation of the number of cellulose chains in it is readily accomplished.

Discussion

The most interesting observations recorded in Table III are the sharply defined differences between the native and regenerated fibers, the former always having the much longer and larger crystallites.

There is also a very close relationship between the observed length of the crystallites and the chain length as calculated from the cuprammonium viscosity as measured with the sample in the "leveling-off" state of hydrolysis when carried out under very specific conditions [3].

In order to interpret these results, it is necessary to review briefly current theories of cellulose structure. The "fringed micelle" theory [9] of cellulose structure offers the most satisfactory explanation of cellulose breakdown under the influence of both ultrasonic vibrations and acid hydrolysis. This theory postulates that there are regions of both the crystalline and amorphous states, the size of these areas being such that a single cellulose chain may pass through both types of structure. If cellulose is subjected to ultrasonic disintegration, then one would expect the type of fibrils to be influenced by (1) the size of the crystalline areas and (2) the degree of orientation.

The role of orientation and crystallinity during the disintegration of regenerated fibers is best illustrated by the behavior of Fortisan and textile rayon spun with a low stretch. Fortisan, the x-ray diffraction pattern of which shows the highest degree of crystallinity and orientation exhibited by any of the regenerated fibers, breaks up into very long fibrils; low-stretch textile rayon, with orientation and crystallinity both of low order, breaks up into very short fibrils of different lengths, and short fibrils may exist in the same fiber when it is disintegrated in the untreated state.

When cellulose is subjected to acid hydrolysis the effect is to shorten the chain length by breaking the 1–4 glucosidic linkages. The cuprammonium fluidity [2, 3] of cellulose offers a convenient means for following the effects of such treatment on the chain length or degree of polymerization of cellulose fibers. Under rather mild conditions [2, 3]—*i.e.*, boiling with 2.5*N* HCl—a condition of nearly constant cuprammonium viscosity is reached and is maintained for quite an additional time of treatment. The chain lengths so obtained are termed "limiting degree of polymerization" (L.D.P.). From a consideration of cellulose structure it can be postulated that the chains most subject to attack during acid hydrolysis would be those in the amorphous or fringed areas of the fiber, the less accessible crystalline areas being relatively unaffected. This picture would account for the close correlation, shown in Tables II and III, between the observed crystallite length and that calculated from the L.D.P. It would also permit the further postulation that the crystallite size in the L.D.P. material is closely related to the crystallite dimensions of the original fiber.

It must be recognized, however, that during hydrolysis some recrystallization could take place since the breaking of the chains in the amorphous areas would leave the broken ends free to rotate, and, under the plasticizing influence of both heat and the presence of water, would tend to extend the already formed crystallites. This view is supported by the relatively small weight loss which accompanies the rapid drop in viscosity [10]. Recrystallization could also account for the slowing down of the rate of hydrolysis for the reason that only the surface of the crystal would then be subject to this kind of attack. From these considerations it is thought advantageous to call the material observed after the acid treatment "hydrolysis crystallites." Justification for the use of this term is strengthened by the fact that x-ray examination of the residue of cotton after treatment by mild acid hydrolysis and ultrasonic vibrations showed it to be in a highly crystalline state.

The much smaller size of the crystallite in the regenerated fibers, with its greatly increased surface as compared with that of the native fibers, may possibly explain the difference in water sorption of the hydrolyzed samples from the dry state under standard humidity conditions as reported by Howsmon [6].

Although the "hydrolysis crystallite" is probably not the exact size and shape of the original crystalline portion of the fiber, nevertheless, from the above considerations one would expect its dimension to be a reflection of the original form of the cellulose crystallite.

Acknowledgment

The author wishes to gratefully acknowledge the kindness and cooperation of Mr. O. A. Battista, who made available the hydrolyzed samples and the data

on their "leveling-off D.P.," and also to Dr. John A. Howsmon for his x-ray examination of some of the samples used in this investigation.

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Investigation on the Differences Between Physical Properties of Skin and Core in Viscose Rayon

Using the Peeling-Off Method Suggested by Elöd

P. H. Hermans

Communication No. 65 from the Institute for Cellulose Research of the AKU and Affiliated Companies, Utrecht, Netherlands

1. Introduction

It seems to be of considerable interest to seek conclusive evidence on the nature of the radial structural gradient existing in viscose rayon filaments. It is well known that staining experiments on cross sections demonstrate that the majority of commercial viscose rayons have a cortical layer which differs markedly in behavior towards dyestuffs as compared with that of the substance in the core and which is separated from the latter by a rather sharp boundary [5, 12]. The thickness of this cortical layer, usually called the skin, varies according to the spinning conditions, and it is also known that its occurrence is dependent upon the presence of zinc salts (or certain other bivalent cations) in the spinning bath [12].

The present investigation is part of a program of research concerned with the phenomenon of the skin-core differentiation. This study does not deal with the cause of that phenomenon but merely with the observable differences in physical properties between skin and core, such as density, swelling power, and orientation.

As a method of approach the technique recently suggested by Elöd and coworkers [1] (*cf.* [14]) is applied. It consists of converting the outer layer of the filaments into triacetate by topochemical acetylation in an indifferent solvent, followed by removal of the acetylated layer by dissolution in a solvent for triacetate. By making the acetylated layer thicker and thicker, or by repeating the operation, a progressive peeling-off of the filament is effected. Elöd used this technique to investigate density and swelling as functions of the degree of peeling-off. He

claimed that in ordinary viscose rayon (so-called Müller-bath-type fibers) the density decreased and the swelling increased towards the core. In the particular example given the change in density was from about 1.517 to 1.510 and the increase in swelling was from about 90% to 125%. Elod and Fröhlich (in cooperation with Zahn) also found that the orientation of the fiber substance (as deduced from x-ray exposures) slightly decreased towards the core.

In view of the importance of reliable information of this kind, a reinvestigation seemed justified, especially since Elod has published his work in summary, without giving all the details necessary for reproduction of the experiments, and since the correctness of his results have been doubted [15]. In addition we wish to remark that a density as high as 1.58–1.60, as calculated by Elöd from his experiments for the cortical layer in viscose rayon, cannot be accepted as correct.

It was therefore decided to undertake the painstaking work of applying Elöd's technique to some typical viscose rayons under conditions controlled as precisely as possible and to examine the peeled-off fibers by various physical methods. Density, swelling power, refractive index, birefringence, and orientation according to x-ray exposures were measured. Some x-ray measurements of crystallinity were also included.

In general, Elod's results can be reproduced, with the exception that for viscose fibers we observed an increase in density instead of the decrease reported by Elod.*

It was found that the acid catalyst employed in the acetylation affects to a certain extent the properties of the treated fibers. In order to account for this fact, which was apparently ignored by Elöd, numerous control experiments were carried out.

2. Experimental Procedure

A. Survey

Our investigations consisted of: (*a*) studying various acetylation conditions and mixtures; (*b*) following the course of heterogeneous acetylation with suitable dyeing tests on cross sections and observing the dissolution of the acetate layer under the microscope; (*c*) determining the loss in weight after peeling-off the acetate layer by dissolution; (*d*) investigating the penetration of the acid catalyst into the fiber core; (*e*) measuring the physical properties as a function of the degree of peeling-off.

B. Apparatus Used for Acetylation

About 50–100 mg. of rayon yarn (total length dependent upon denier), desized and cleaned in hot 1% sodium carbonate solution, was loosely wound on the glass frame which is sketched in Figure 1A (left). The frame was then lowered into the acetylation mixture in the vessel shown in Figure 1B (right). In order to keep the temperature of the mixture constant, a liquid with the proper boiling point was allowed to boil in the outer part of the apparatus. The reaction terminated, the glass frame was taken out of the vessel, rinsed consecutively with benzene, alcohol, and water, then immersed in distilled water containing some ammonia, and then treated with boiling water for about 2 min.

Finally, the fibers were after-treated with hot baryta water (see section C), washed with water, and allowed to dry in the air at room temperature.

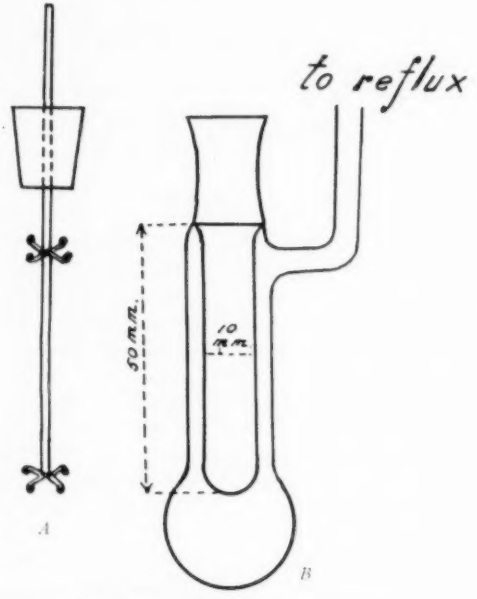


FIG. 1. *Apparatus used in acetylation.*

* We also have reason to disagree with the existence of a general negative correlation between density and swelling power in cellulose fibers, which was particularly emphasized by Elod.

C. Acetylation Procedure

In conformity with Elöd's method, the best results were obtained by using air-dry fibers in the acetylation mixture. If the fibers are preswollen in water or pretreated with glacial acetic acid after immersion in water, the acetylation proceeds much more rapidly but also in too irregular a fashion, which is unsuitable for the purpose under consideration. Several acetylation mixtures and temperatures were tried, from which 3 successful combinations were derived:

	Method *A*	Method *B*	Method *C*
Temperature (°C)	76° (b.p. CCl_4)	76° (b.p. CCl_4)	40° (b.p. CH_2Cl_2)
Acetic anhydride (ml.)	10	10	12
Toluene (ml.)	40	40	45
Catalyst (ml.)	0.025 (H_2SO_4)	0.025 ($HClO_4$)	0.11 (H_2SO_4)

Freshly prepared mixtures should be employed. Use of pure, dry toluene which is free from sulfur compounds is essential, and the acetic anhydride should contain a minimum amount of acetic acid. If too much acetic acid is present (as in repeatedly re-used mixtures) acetylation tends to proceed irregularly.

C is essentially the mixture recommended by Elöd. The acetylation velocities for these mixtures are roughly in the proportion $A : B : C = 5 : 25 : 1$; hence, the reaction times necessary to effect a given degree of conversion are in the inverse proportion.

For all of the mixtures the tensile strength of the fibers (before as well as after peeling-off) decreased considerably with time of treatment. This phenomenon is due to attack of the cellulosic substance by the acid catalyst, and, contrary to Elöd's belief, no conclusions are permitted as to a possible radial gradient of tensile strength inherent in fiber structure.

Attempts to avoid this deterioration of the fiber were unsuccessful. True, heterogeneous acetylation can also be attained by using acetic anhydride dissolved in an aromatic hydrocarbon with potassium acetate as a catalyst. A typical mixture of this kind was 1 g. potassium acetate dissolved in a warmed-up mixture of 1 ml. glacial acetic acid, 4 ml. acetic anhydride, and 6–8 ml. toluene at 100°C.

Fiber strength is not decreased in this mixture, but no solvent could be found which would completely remove the acetate shell. The latter merely swells in the usual solvents but does not readily dissolve. Therefore, one is compelled to use the acid catalysts and to accept the then inevitable fiber deterioration.

We shall see below that some properties other than tensile strength are also affected by the acid catalyst.

D. Peeling-Off the Acetate Layer

The solvent used for removing the acetate layer was a mixture of 85 ml. chloroform and 15 ml. methanol. This mixture rapidly and quantitatively removes the acetylated skin, a process which can be followed under the microscope when treating fibers or cross sections with the solvent. After applying the fresh solvent twice, followed by rinsing with water, the fibers are inert towards typical acetate dyestuffs such as Celliton Red and Celliton Blue, which readily stain the acetylated fiber skin before peeling-off.

In order to remove residual acetate groups (possibly present) from the fiber surface, we took the precaution of after-treating the peeled-off samples with boiling 0.3*N* barium hydroxide solution for 1 hr. In a similar experiment with a fiber still bearing the acetate skin, the treated fiber became inert towards boiling Celliton Red suspension, showing that the acetate layer was actually saponified.*

E. Microscopical Control of the Process

Microscopical examination of fiber cross sections proved to be essential in order to establish correct conditions and to direct operations properly.

Figure 2A shows sections of a cord rayon which had been acetylated for 17 hrs. (method *A*), stained with Victoria Blue. The acetylated layer remained unstained; the core was dyed a deep blue. If these sections are washed with 89% alcohol according to the prescriptions given for differential staining of the skin proper [15] (Figure 2B), it is seen that the inner part of the skin (which retains the blue dye) has still escaped acetylation.

Figure 2C shows the sections of the same fiber, cut after dissolving off the acetate layer and applying the differential Victoria Blue staining procedure.

In Figure 3 sections are shown of cord rayon which had been acetylated for only 4 hrs. (method *A*). The sections were dyed with Victoria Blue and

* The boiling with barium hydroxide should not be extended beyond 1 hr., since then the typical dyestuff retention of the original skin substance is affected and the microscopical control procedure described in section *E* becomes uncertain. If boiling is prolonged to 2½ hrs. the skin bleeds off almost as rapidly as the core does in the Victoria Blue test.

A *B* *C*

FIG. 2. *A—Cross sections of a cord rayon which had been acetylated for 17 hrs. (method A); stained with Victoria Blue. B—Same sections after washing with 89% alcohol, showing that acetylation has not proceeded beyond the skin proper. C—Sections of same fiber after dissolving the acetate layer with the $CHCl_3$-CH_3OH solvent.*

washed with 89% alcohol until discoloration of the core occurred. The acetate layer still being very thin, it was hardly visible in the ordinary microscope.

The micrograph reproduced in Figure 3 was taken with the phase contrast microscope. The thin outer shell of cellulose acetate then becomes nicely visible as a thin, very bright layer. The picture demonstrates that the acetylation proceeds quite uniformly.

If the sections of acetylated fibers are treated with a hot suspension of Celliton Red, the acetate layer is stained red, whereas the fiber core remains unstained.

If partly acetylated fibers of the type shown in Figure 2 are saponified with boiling baryta water and the cross sections are differentially stained with Victoria Blue, it is seen that the acetylated and saponified layer of the skin no longer retains the dye. Obviously, the particular skin structure is destroyed upon acetylation followed by saponification.

If acetylation is carried on much longer than 24 hrs. with the fibers shown in Figure 2, it is seen that the acetylated layer begins to show more and more radial flaws (Figure 4), while after still longer reaction times the acetylation proceeds in a more and more irregular fashion. Finally, the filaments tend to fall apart into fibrillar fragments.

In order to avoid difficulties of this kind, it was necessary to set a limit to the reaction time. In order to proceed deeper into the fiber, the fiber was peeled-off with the solvent and then exposed a second time to the acetylating mixture for a similar period, and so on.

By this procedure of repeated acetylation followed by peeling-off, the cortical layer of the fiber which is indicated by the Victoria Blue test as being the "skin" could readily be almost entirely removed in all instances investigated.

If, however, acetylation was then carried on in order to proceed beyond the skin, it was usually found that the reaction became more rapid and penetration became very irregular. Upon subsequent dissolution of the acetate layer, the filaments on the glass frame then showed numerous breaks. Yarn

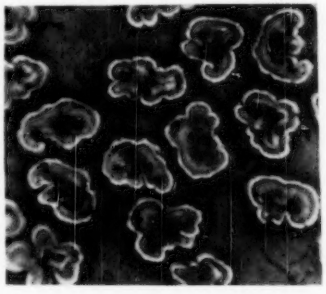
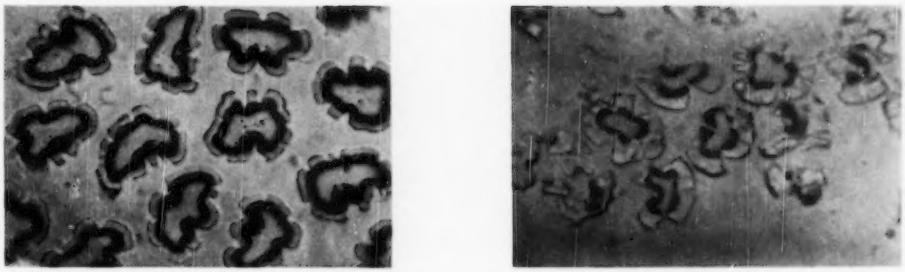


FIG. 3. *Cross sections of the same rayon as in Figure 2, acetylated for 4 hrs. (method A) after differential staining; taken with the phase contrast microscope. Thin acetate layer shows up bright.*



A *B*

FIG. 4. *Same rayon as in Figure 2; prolonged acetylation (method A). A—After 24 hrs. B—After 48 hrs. (Differentially dyed with Victoria Blue.)*

fringes of irregular length instead of continuous-filaments were then re-collected from the frame.

It seems that the tendency to acetylate more rapidly and in an irregular fashion is an attribute of the fiber core, in contrast to the capacity of the skin to acetylate layerwise and neatly.

In later experiments we sometimes succeeded in proceeding with the acetylation considerably beyond the skin without obtaining breaks or weak spots in the yarn wound on the frame. The samples of the very central part of the fibers thus obtained have been included in the examination of the physical properties referred to below. We have, however, failed to control the conditions responsible for this incidental success.

Figure 5 shows an example of such a case. The material is a cord rayon from which 72% of the substance had been peeled-off (*cf.* Table II). The micrograph was taken with the phase microscope in order to improve the contrast between the sections and the imbibition medium.

An example of a progressive acetylation and peeling-off experiment, just removing the fiber skin, is shown by the series of micrographs in Figure 6. The specimen was an ordinary textile rayon (designated as "textile rayon I" in Tables II and III) which had been dulled with titanium dioxide. According to the Victoria Blue test (Figure 6A) this fiber possessed a thinner skin than that shown in the preceding micrographs. The sections were embedded in a medium with almost the same refractive power, so that the cellulose is visible only where it is stained or where its presence is revealed by the particles of the pigment. It is seen in Figure 6C that only a few small fragments of the stained skin remained.

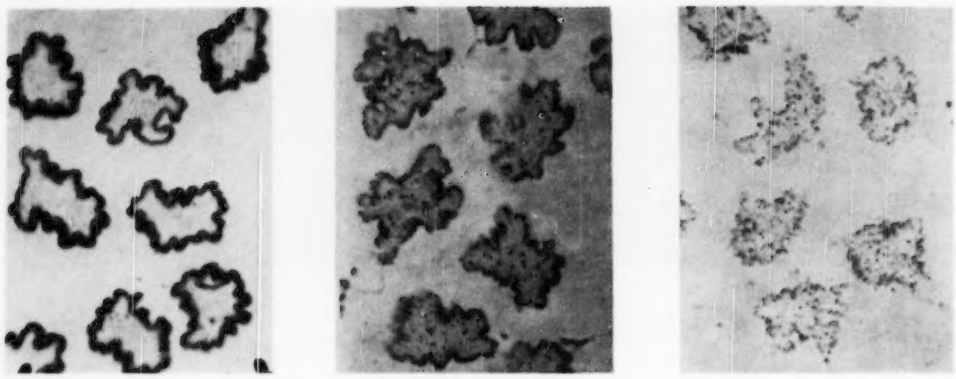
Finally, Figure 7 shows sections of another rayon, designated as "textile rayon III" in Tables II and III. *A* shows sections of the original fiber (the skin stained with Victoria Blue); *B* shows sections of the same fiber after it had been treated for 4 days (method *C*) and subjected to the Victoria Blue test. Since the fibers were not treated with solvent, the acetate layer was still present, but all the dye had disappeared, demonstrating that acetylation had proceeded beyond the skin.

FIG. 5. *Sections of cord rayon which had been peeled-off 72%. (Phase contrast microscope.)*

The sample series used for final physical examination in this investigation consisted of treated fibers, meticulously controlled by the microscopical staining methods set forth above. It was attempted to bring the last member of each series as near as possible to the condition pictured in Figure 6C (skin just about removed).

F. Measuring Degree of Peeling-Off and Reaction Rate

The percentage of fiber substance removed was determined by weighing a known length of condi-



A *B* *C*

FIG. 6. *A—Textile rayon I before acetylation. B—Same rayon acetylated (method C, 48 hrs.) and peeled-off. C—Same rayon acetylated (method C; 2 × 48 hrs.) and peeled-off.*

tioned yarn before and after the peeling-off operation. In some cases the value obtained was compared with microscopical measurements of cross-sectional surfaces. Although these operations were somewhat tedious and not very accurate, we could thus convince ourselves of the approximate conformity between the two results.

These measurements also afford some idea as to the course of the reaction. It seems that the rate of penetration is governed merely by the velocity of the acetylation at the surface of the cellulose exposed and not by the diffusion velocity of the reagent through the acetylated layer towards the locus of the reaction.*

If the amount of cellulose acetylated per unit of time is proportional to the surface of cellulose exposed and, for a given fiber and a given reagent, is not determined by other factors, it can easily be shown that

$$r_o(1 - \sqrt{g_t/g_o}) = kt, \qquad (1)$$

where r_o is the radius of the original fiber, g_o and g_t are the fiber weights per unit fiber length at times 0 and t (after peeling-off), and k is a constant characteristic for the system. If A is substituted for g_t/g_o, then $(1 - \sqrt{A})/t$ is a constant.

In Table I some observations are evaluated according to this formula. The last column shows that $(1 - \sqrt{A})/t$ is a constant, as a first approximation, for each series. As shown by the single case where more than 50% of the fiber substance had been removed (cord rayon II, method *B*, 4 hrs.), the reaction velocity tends to increase towards high degrees of peeling-off when the Victoria Blue skin is surpassed (it was found in this case, by measuring stained cross sections, that the skin comprised nearly 50% of the cross-sectional surface).

G. Penetration of the Acid Catalyst into the Fiber Core

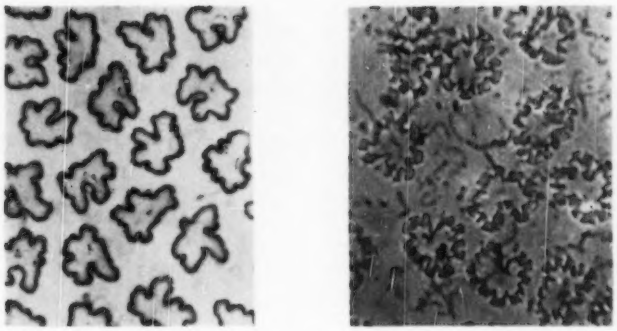
The already mentioned gradual deterioration of fiber strength during the reaction led us to suspect

TABLE I. EVALUATION OF EQUATION (1) (*t* REACTION TIME; *A* RELATIVE WEIGHT AFTER PEELING-OFF (RESIDUAL CELLULOSE))

	t (hrs.)	*A**	$\sqrt{A}$	$(1-\sqrt{A})/t$ $(=k/r_o)$
Cord rayon I (method *A*)	9	0.837	0.915	0.0095
	17	0.663	0.815	0.011
	2×17	0.535	0.732	0.008
Cord rayon II (method *B*)	0.5	0.994	0.998	—
	1	0.902	0.950	0.05
	2	0.786	0.886	0.06
	2× 2	0.412	0.642	0.09
Cord rayon II (method *C*)	48	0.795	0.892	0.054
	96	0.688	0.830	0.042
	2×72	0.562	0.750	0.042
Textile rayon I (method *C*)	48	0.86	0.927	0.036
	96	0.76	0.872	0.032

* Fraction of unattacked fiber.

* The same result was reached earlier by O. Kratky in an unpublished report referred to at the end of this paper (see page 567)



A B

FIG. 7. *A—Textile rayon III before acetylation. B—Same rayon acetylated (method C, 4 days). Acetate layer not removed.*

that the mineral acid which is used as a catalyst might diffuse into the fiber core beyond the acetylated layer and there attack the cellulose. This presumption was confirmed by microscopical observations on fibers which had been previously dyed to saturation with Congo red as an indicator. After exposure to reaction mixture *A* for 17 hrs. the yarn, washed with benzene and 96% alcohol, was sectioned and examined. The Congo red in the center of the fibers showed a mauve color which was markedly different from the neutral shade and which corresponded to a pH of about 4; after treatment with dilute sodium bicarbonate, the color changed to orange-red, indicating that unreacted acid had penetrated into the core.

The diffusion of acid into the cellulose is also corroborated by the control experiments in which a toluene solution of the acid catalyst was allowed to act on the fibers under identical conditions of time and temperature (see page 560).

H. Determination of Density and Refractivity

Density of the completely dry fibers and their refractive indices for light polarized parallel with and perpendicular to the fiber axis were determined according to standardized methods which have been published in detail [3, 7].

I. Determination of Swelling

A micromethod was used. About 20 mg. of the yarn in question was cut into lengths of 1.5–2 cm. A pellet was formed from the cut fibers by rolling them between thumb and forefinger. Parallel alignment of the single fibers is thus disturbed almost completely.

The pellet was soaked in distilled water for 2 hrs. and then introduced by means of forceps into the inner tube on top of the glass ball of the apparatus shown in Figure 8. The apparatus was then placed in an ordinary laboratory centrifuge and was centrifuged for 10 min. at 2,500 r.p.m. The pellet was then quickly removed, placed into a closed weighing vessel, and weighed. After that the pellet was dried at 110° C and weighed again.

The degree of swelling is the weight of the water in percent of the dry weight of the pellet. Two to six determinations were made and the results were averaged.

For absorbent cotton, 57% was found; for several rayons, values ranging between 85% and 95%, in good conformity with macrodeterminations reported in the literature, were found. The experimental error is estimated to be about 5%.

The swelling values, however, may in some degree be dependent upon fiber denier, a factor which has remained beyond control. We therefore cannot ascribe great precision to these values.

3. Experimental Results

The fibers selected for investigation were a tire-cord rayon with a thick skin and 3 textile rayons, designated as I, II, and III, with relatively thin skins. No. I was a commercial, semidull yarn containing titanium dioxide; No. II and No. III were experimental yarns spun from ordinary low-alkali viscose in an ordinary bath with no stretch and with

70% stretch (applied in a second hot bath), respectively.

The x-ray results require separate treatment (see section 5). The other physical properties studied in relation to increasing degree of peeling-off are given in Table II, in which are listed the percentage of substance removed, the principal refractive indices in the bone-dry condition, the average refractive index $n_{\infty} = \frac{1}{3}(n_{\parallel} + 2n_{\perp})$, the birefringence, the density calculated from n_{∞} and the density determined directly, the orientation factors * as derived from birefringence and those determined from x-ray diagrams (see also section 5), and, finally, the percentage of swelling.

It has been shown [3, 7] that if d is the density, as determined after the method used in this investigation, then the quantity $(n_{\infty} - 1)\,d$ is a constant for all cellulose fibers, amounting to 0.3570. With the aid of this constant the "calculated densities" were computed from n_{∞}. In the majority of cases they check well with the observed densities. It is our experience that the experimental error in densities calculated from refractive power is smaller than that in the densities measured directly. If the relative density of various samples is of interest, the optical densities represent the more precise values.

In Table III a number of observations are recorded for experiments which were carried out as controls. The other experiments served for studying the effect of the acid catalyst on the fibers under conditions comparable to those prevailing in the acetylation experiments—however, in the absence of acetic anhydride, for which was substituted an equal volume of dry toluene.†

In Table IV are given the mechanical properties of a tire-cord rayon peeled-off to various degrees, using the 3 different acetylation procedures with an acid catalyst mentioned in section 2C. Tenacities and elongations are averages of 25 single-fiber tests; the denier values are averages of 50 determinations using the vibroscopic method.

Table V gives mechanical properties of 2 rayons before and after acetylation with a nonacid catalyst (potassium acetate). Filament denier, of course, increases with acetylation. Since in this case the

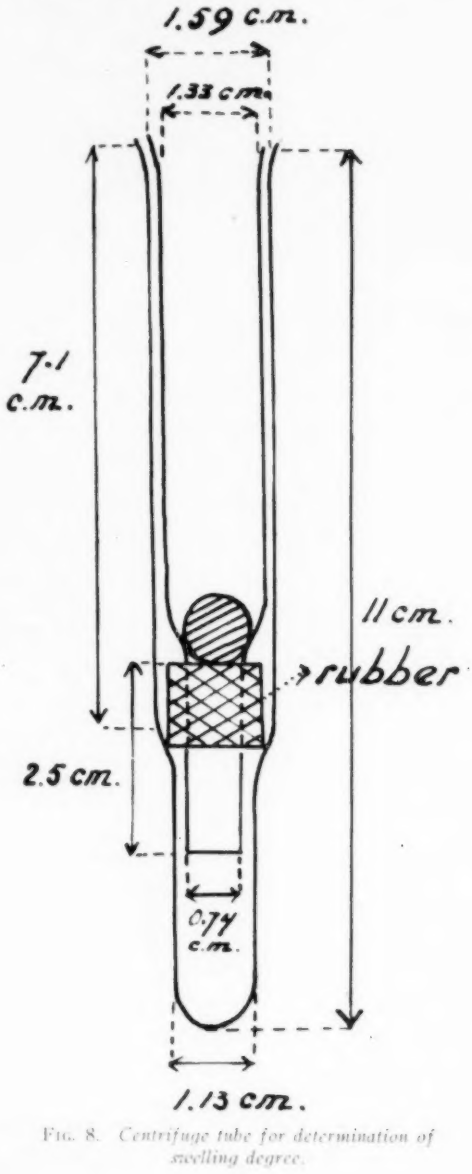


FIG. 8. *Centrifuge tube for determination of swelling degree.*

* It is recalled that the orientation factor is zero for the isotropic state and reaches the value of 1 at complete orientation. The optical orientation factor f_o is found by dividing the birefringence of the fiber by 0.050 (see [3, 7]). It represents a measure of the over-all orientation of the fiber substance. The x-ray orientation factor f_x is obtained by quantitative evaluation of the x-ray diagram [3, 7]. It represents an absolute measure of the orientation of the crystalline portion of the fiber substance.

† After the acid treatment the fibers were washed and treated for 1 hr. with boiling barium hydroxide in exactly the same way as after the acetylation experiments.

TABLE II. OPTICAL PROPERTIES, DENSITY, ORIENTATION, AND SWELLING AS FUNCTIONS OF DEGREE OF PEELING-OFF

Specimen	Reaction time	Amount peeled-off (%)	Refractive indices $n_{\parallel}$	$n_{\perp}$	$n_{av.}$	Double refraction $\times 10^3$	Density: Calculated from $n_{av.}$	Density: Determined directly	Orientation factors: Optical (f_o)	Orientation factors: X-Ray (f_x)	Swelling (%)
Cord rayon II	0	0	1.566[a]	1.527[f]	1.540[k]	37.7	1.514	1.516	0.77	0.89[d]	85
Method *C*	2 days	20.5	1.566[a]	1.530[g]	1.542[k]	35.5	1.519[k]	1.520[k]	0.71	0.89[d]	85
	4 days	31.2	1.566[a]	1.531[k]	1.543[g]	34.5	1.521	1.522	0.69	0.89[d]	86
	2+2+2 days	43.8	1.566[a]	1.532[g]	1.543[g]	33.8	1.522[g]	1.523	0.67[k]	0.89	87
	—	>60	1.568[f]	1.533[g]	1.545[g]	35.7	1.526[k]	—	0.71	—	—
Method *C'*	3+2 days	56.6	—	—	—	—	—	—	—	—	104
	—	72	1.568[k]	1.532[g]	1.544[g]	36.3	1.524[k]	1.523[k]	0.72	—	136
Method *B*	2 hrs.	21.4	1.567[a]	1.529[g]	1.541[k]	37.7	1.517	1.521	0.75	—	84
	2+2 hrs.	58.8	1.567[k]	1.531[k]	1.543[g]	36.0	1.522[g]	1.523	0.72	0.89[d]	83
Textile rayon I	0	0	1.588[a]	1.536[a]	1.543[k]	22.0	1.522[k]	1.520	0.44	—	92
Method *C*	2 days	14.0	1.558[f]	1.537[g]	1.544[k]	21.4	1.525	1.525	0.43	—	81
	4 days	24.1	1.558[a]	1.538[k]	1.544[g]	19.7	1.526[k]	1.527	0.39	—	80
	4+2+2 days	~50	1.558[f]	1.538[a]	1.545[g]	20.0	1.527[k]	—	0.40	—	84
	4+2+3 days	>50	1.558[a]	1.538[f]	1.545[k]	19.3	1.526[k]	—	0.38[k]	—	—
Textile rayon II	0	0	1.544[a]	1.534[g]	1.541[k]	19.1	1.516	1.518	0.38	0.62	75
Method *C*	4 days	50.0	1.544[k]	1.541[a]	1.545[k]	13.5	1.528	1.526	0.27	0.58[k]	119
Textile rayon III	0	0	1.568[k]	1.531[k]	1.543[g]	37.1	1.523[k]	1.525	0.74[k]	0.86	73
Method *C*	4 days	58.5	1.571[g]	1.536[a]	1.548[a]	35.9	1.535	1.536	0.71[k]	0.83[k]	106

acetate layer was not removed (see section 2*C*), and since the absolute strength is the value of interest, the tenacities of the acetylated fibers were calculated using the denier of the fiber before acetylation.

4. Discussion

The deterioration of the fibers owing to the use of an acid catalyst (already mentioned in section 2*C*) is indicated by the data in Table IV. Tenacity and elongation decrease with increasing time of treatment. (Table V shows that no such deterioration takes place if potassium acetate is used as the catalyst.)

Unfortunately, the use of an acid catalyst (which is required in order to render the peeling-off successful) limits the usefulness of Elöd's method for the study of the difference in properties between skin and core. In particular, it affords no information on the possible existence of a radial gradient in mechanical properties.

It is safe to assume that slight chemical attack on the fiber by the acid catalyst will not greatly affect its orientation. However, conclusive evidence on density and swelling—properties which may be affected by the action of the acid—will be difficult, if not impossible, to obtain and will require special consideration.

As to orientation, Table II shows that in all of the cases investigated the birefringence decreases towards the center of the fiber. This is graphically illustrated in Figure 9; this effect is in conformity

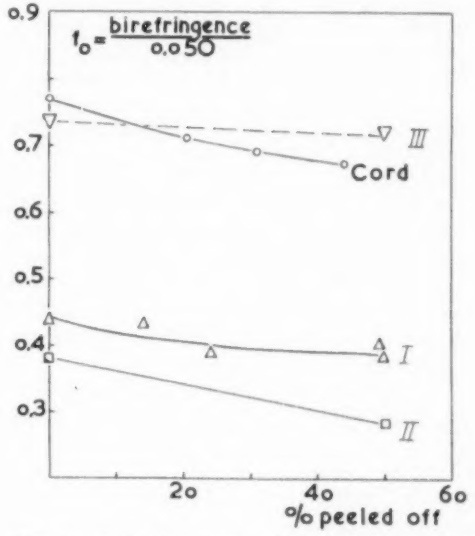


FIG. 9. *Optical orientation factor as a function of degree of peeling-off.* (*Cord rayon and textile rayons I, II, and III.*)

TABLE III. OPTICAL PROPERTIES, DENSITY, AND SWELLING OBSERVED IN VARIOUS CONTROL EXPERIMENTS WITHOUT PEELING-OFF (TEMPERATURE AND ACID CONCENTRATION SAME AS IN METHOD *C*)

Specimen	Time of treatment (days)	Refractive indices $n_{\parallel}$	$n_{\perp}$	n_{av}	Double refraction $\times 10^3$	Density Calc. from n_{av}	Density Det'd. directly	Swelling (%)
Cord rayon II								
Untreated	—	1.566[0]	1.527[7]	1.540[9]	37.7	1.514	1.516	85
Partial acetylation followed by:								
(*a*) Saponification in 0.3*N* $Ba(OH)_2$ at 100° C*	4	1.566[7]	1.529[6]	1.541[9]	37.2	1.518	—	—
(*b*) Saponification in 4*N* NH_3 at 100° C	4	1.564[8]	1.529[9]	1.540[8]	35.5	1.515	—	—
Treatment without acetic anhydride (acid catalyst alone in toluene)	4	1.565[8]	1.528[8]	1.540[7]	37.1	1.515	—	—
Treatment without acetic anhydride (acid catalyst alone in toluene)	4	1.565[2]	1.528[8]	1.540[9]	36.4	1.515	—	—
Treatment without acetic anhydride (acid catalyst alone in toluene)	6	1.567[2]	1.529[2]	1.541[8]	38.0	1.518	1.516	60
Treatment without acetic anhydride (acid catalyst alone in toluene)	8	1.566[0]	1.528[8]	1.540[8]	37.5	1.515	—	—
Treatment without acetic anhydride (acid catalyst alone in toluene)	8	1.566[3]	1.529[8]	1.541[7]	36.6	1.517[8]	—	—
Textile rayon I								
Untreated	—	1.558[0]	1.536[0]	1.543[3]	22.0	1.522	1.520	92
Acid catalyst alone	4	1.558[5]	1.536[0]	1.544[0]	21.7	1.524	—	—
Acid catalyst alone	6	1.558[0]	1.535[7]	1.543[1]	22.3	1.521	—	57
Acid catalyst alone	8	1.558[3]	1.535[8]	1.543[8]	21.7	1.522	—	—
Acid catalyst alone	8	1.559[8]	1.537[0]	1.544[8]	22.5	1.525	1.526	—
Textile rayon II								
Untreated	—	1.554[0]	1.534[3]	1.541[3]	19.1	1.516	1.518	75
Acid catalyst alone	4	1.555[2]	1.535[8]	1.542[8]	19.4	1.519	1.517	76
Textile rayon III								
Untreated	—	1.568[5]	1.531[8]	1.543[8]	37.1	1.523[9]	1.525	73
Acid catalyst alone	6	1.571[8]	1.532[2]	1.545[3]	39.3	1.527	1.522	70

* (*a*) and (*b*) refer to partially acetylated samples which were saponified without previous peeling-off.

with previous findings (or beliefs) of other authors [12, 13, 16]. The magnitude of the effect is, however, not very large.

Decrease of orientation towards the core is also corroborated by the x-ray experiments for textile rayons II and III (see Figure 10). (Textile rayon I was not investigated owing to the presence of titanium oxide, which might affect the accuracy of the measurements.) In the cord rayon, the x-ray orientation factor remains unchanged.

Decrease in birefringence implies a decrease of $n_{\parallel}$ accompanied by an increase of $n_{\perp}$ and a constant value of n_{av} if the density remains constant. Considering the relevant values in Table II, it is seen that in all cases investigated $n_{\parallel}$ remains almost constant while $n_{\perp}$ and n_{av} definitely increase. This can only mean an increase in density, as is illustrated by the densities calculated from n_{av} and by the densities determined directly. The course of these density values is graphically represented in Figure 11 for cord rayon and for the textile rayons I, II, and III.

Evidence as to whether the density increase is a real structural feature or whether it is an artifact due

TABLE IV. MECHANICAL PROPERTIES OF PEELED-OFF CORD RAYON FIBERS, USING AN ACID CATALYST

	Reaction time	Denier	Amount peeled-off (%)	Strength Dry (g./den.)	Strength Wet (g./den.)	Elongation Dry (%)	Elongation Wet (%)
Method *A*	0	2.56	0	3.27	2.11	21	27
	9 hrs.	2.08	19	2.18	1.13	13	15
	17 hrs.	1.13	56	1.85	1.12	19	23
	17+17 hrs.	1.36	47	1.33	0.50	8	10
Method *B*	1.5 hrs.	1.01	60	1.88	0.96	14	17
	3 hrs.	1.28	50	1.73	1.26	13	19
Method *C*	3 days	1.85	28	2.40	1.59	16	26

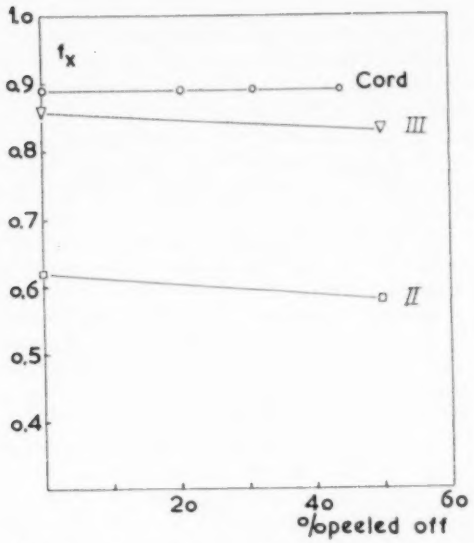


Fig. 10. *X-ray orientation factor as a function of degree of peeling-off.*

to the action of the acid catalyst is given by the control experiments recorded in Table III. The data show that little or no density increase was observed if partially acetylated fibers were saponified back to cellulose without previous peeling-off.

This also holds for the numerous still more significant experiments recorded in which the fibers were treated with a toluene solution of the acid catalyst alone under identical conditions. The maximum increase ($\times 10^{-4}$) of (optical) density observed for the various specimens is summarized below:

	Cord	Textile I	Textile II	Textile III
Peeling-off (Table II)	12	5	12	11.5
Acid treatment (Table III)	4	3	3	3.5

Thus, it would seem that the density gradient is real.*

Although there is no doubt as to the correctness of the observed densities (the figures obtained with 2 independent methods checking well with each other), the question may still be raised as to whether the density was affected by the operations to which the fibers were subjected and whether the control experiments referred to in Table III presented sufficient proof that it was not. Independent evidence of the existence of a real density gradient seems, therefore, desirable. Such evidence seems to be furnished from electron micrographs of thin sections of a tire-cord rayon, which show the occurrence of numerous tiny gas enclosures, measuring about 0.2 micron and smaller, in the "skin" part of the section.

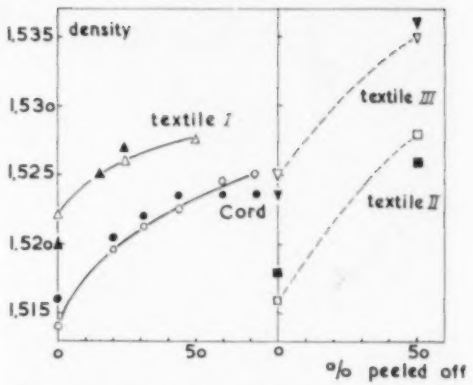


Fig. 11. *Density observed by flotation method (black symbols) and computed from optical data (open symbols) as functions of peeling-off.*

Further details of this work will be published separately. A picture of this kind was published earlier in a Letter to the Editor of this Journal (February, 1950, issue, page 105). It is reproduced in Figure 12.† If the accumulation of vacuoles of this kind in the skin is a general phenomenon in viscose rayon, it might explain the observed density gradient. (The investigation of other specimens is still in progress.) If we venture to calculate the density of the removed skin from the density of the original fiber, d, and the observed density, d_c, of the core (less 4×10^{-4}, correcting for the average error due to the acid treatment), the following equation should be used:

$$1/d - (1 - x)d_c = x/d_s.$$

* The reported observations on density are in contradiction to those of Elöd and coworkers, who claimed that there is a decrease in density towards the core for fibers of the "Müller-bath type" ([1]; *cf.* [14]).

† The sections were made on an ordinary sledge microtome (Leitz, Wetzlar) according to the method indicated by L. H. Bretschneider (*Proc. Netherl. Acad. Sci.* 52, 654 (1949)). In setting this microtome to cut sections of 1-micron thickness, it appeared that among the sections obtained many were considerably thinner than 1 micron and were thin enough for successful examination in the electron microscope. The author is indebted to Dr. Bretschneider for advice and assistance and to the Institute for Electron Microscopy (Physical Laboratory of the Technical University, Delft) for taking the photographs.

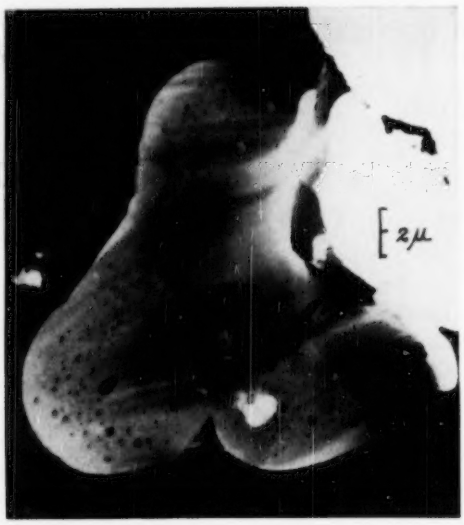


FIG. 12. *Electron micrograph of a cross section of a tire-cord-type viscose-rayon filament. Magnification 5,000×. (The original film was first printed on a diapositive film and a paper print of the latter is here reproduced.)*

where x is the fraction peeled-off and d_s is the density of the skin. The results are listed in Table VI. If the observed density increase is actually due to porosity of the outer layers, the different velocities of acetylation of the rayons referred to in Tables II and III become comprehensible also.

These differences in acetylation velocity are shown in Figure 13; in Figure 14 is plotted the time in days required to reach 30% acetylation against the percentage density increase taken from Table VI. The greater the density increase the greater will be the porosity of the outer layers, and it is seen that the reaction time actually decreases with increasing porosity, thus satisfactorily correlating the observed reaction velocities with the density measurements. (Contrarywise, there is no correlation between reaction velocity and absolute density of either skin or core.)

The correlation between density gradient, electron micrographs, and velocity of acetylation is given with some reservation until further evidence is obtained. In the case of textile rayon III, the density observed for the center of the fiber reached a value as high as 1.535, which is rather surprising since the highest densities previously observed for regenerated cellulose were well below 1.530 (*cf.* [3, 7]).

As to swelling power, less conclusive evidence can be derived from the observations listed in Table II and graphically shown in Figure 15. True, the measurements suggest that in cord rayon swelling remained constant up to 50% peeled-off; in textile rayons II and III swelling was constant up to about 30% peeled-off, and increased at higher degrees of conversion which reached beyond the fiber skin. (Textile rayon I showed little change up to 50%.) However, the control experiments in Table III reveal that swelling may be considerably affected by treatment with acid alone, although in the reverse sense. It seems prudent to forbear from drawing any definite conclusions regarding a radial gradient of swelling power, as has been done by Elöd—the more so because the determination of swelling in turn may be affected by the denier of the filaments (*cf.* section *2f*).

TABLE V. MECHANICAL PROPERTIES OF TWO RAYONS BEFORE AND AFTER PARTIAL ACETYLATION WITH A NONACIDIC CATALYST

	Denier	Strength* Dry (g./den.)	Strength* Wet (g./den.)	Elongation Dry (%)	Elongation Wet (%)
Textile rayon II, not treated	2.25	2.10	1.03	17	21
Textile rayon II, partially acetylated	2.87	2.34	1.20	19	18
Textile rayon III, not treated	5.87	2.37	1.34	31	42
Textile rayon III, partially acetylated	8.80	2.24	1.35	32	36

* Calculated using the denier of the nontreated fiber.

5. Investigation with X-Rays

The aim of this investigation was twofold: to see whether there exists a radial gradient in orientation and whether there is a difference in crystallinity between the outer and central parts of the fiber.

TABLE VI. DENSITY d_s OF SKIN CALCULATED FROM THE OBSERVED DENSITY d_c OF THE CORE

Specimen	x	d	d_c	d_s	Density increase (%)
Cord rayon	0.6	1.514	1.519	1.511	0.53
Textile rayon I	0.5	1.522	1.523	1.522[a]	0
Textile rayon II	0.5	1.516	1.524	1.508	1.05
Textile rayon III	0.6	1.523[a]	1.531	1.519	0.8

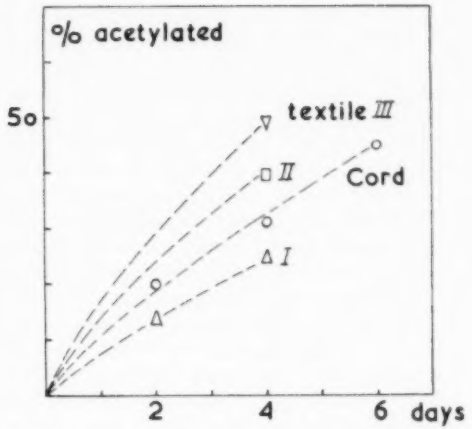


FIG. 13. *Progress of acetylation as a function of time for the rayons referred to in Table II.*

Orientation was studied by taking photographs of well-parallelized fibers with filtered copper radiation and evaluating the diagrams according to a well-established, accurate procedure [2, 3, 6].

Crystallinity determinations were carried out by taking exposures from standardized isotropic fiber pellets with strictly monochromatized copper radiation, using a quantitative technique which had been described previously [8, 9].

The results of the orientation measurements are summarized in Table VII. The quantities $\sin^2\alpha_a$ and $\sin^2\alpha_s$ represent the average squared sines of the orientation angles of the two paratropic planes A_a and A_s (the lamellar plane of the ribbon-shaped crystallites in which the hydrogen bonds lie and the plane nearly perpendicular to it, respectively); $\sin^2\alpha$ represents the average squared sine of the orientation angles of the crystallite fiber axes. The orientation factor f_x (also listed in Table II and graphically presented in Figure 10) is related to these quantities by the equation:

$$f_x = 1 - \tfrac{3}{2}\sin^2\alpha = 1 - \tfrac{3}{2}(\sin^2\alpha_a + \sin^2\alpha_s).$$

For the cord-rayon sample no change in orientation was observed up to the removal of about 60% of the fiber substance.

It is seen that for the two textile rayons, where a gradient of orientation exists, it is mainly, if not exclusively, the orientation of the A_s planes which changes and becomes lower towards the center of the fibers.

A closer analysis of the probable meaning of this observation leads to the conclusion that the difference in orientation between skin and core is due to a different magnitude of tensions or deformations having acted in the *lateral* direction, rather than to a different amount of stretch in the direction of the fiber axis.* Birefringence phenomena observed in rayon cross sections [4] furnish certain evidence in support of this conclusion.

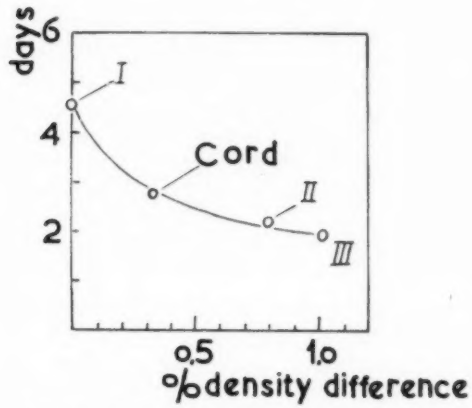


FIG. 14. *Time in days to reach 30% acetylation plotted against percentage difference in density of skin and core (taken from Table VI).*

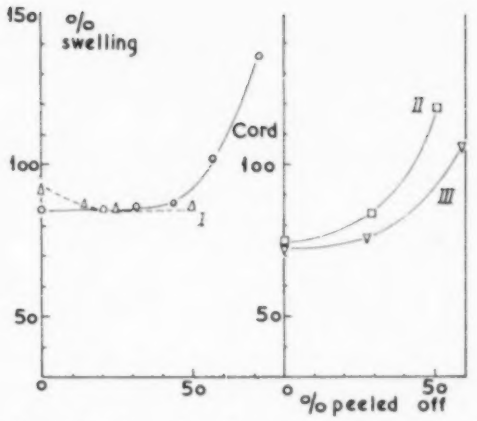


FIG. 15. *Observed swelling power as a function of percentage of fiber peeled off. (Some observations not listed in Table II are included.)*

* As is now well known [3, 7] a different amount of longitudinal stretch in rayon filaments will earlier reveal itself in a different orientation of the A_s (101) planes.

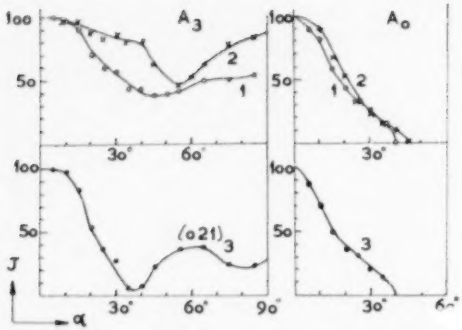


FIG. 16. *Intensity distribution along Debye-Scherrer circles for the interferences* A_3 *(left) and* A_0 *(right) in textile rayon II. Curves 1—Before peeling-off. Curves 2—After peeling-off 50% of the outer layers. Curves 3—Differential curves for the skin.* α = *angular distance from the equator.* J = *intensity.*

From the intensity distribution along the Debye-Scherrer circles on the photograph of the original and that of the peeled-off fiber, the corresponding intensity distribution of the peeled-off skin can be computed. This is of interest for the textile rayons investigated—in particular, for No. II, which was spun without applying additional stretch. The intensity distribution curves (intensity plotted against angular distance from the equator) are reproduced in the upper part of Figure 16 for the A_3 interference (left) and for the A_0 interference (right). Curves numbered 1 refer to the original and those numbered 2 to the peeled-off fiber. In the lower part of Figure 16 the curves numbered 3 are for the skin, as obtained by subtraction of 2 from 1.*

The intensity curve 2 of the A_3 interference for the peeled-off fiber has a quite unusual shape. It is seen, however, that the differential curve 3 obtained from 1 and 2 is entirely normal for a rather well-orientated rayon. (The A_3 interference is just separated from the 021 interference, which lies on the same Debye-Scherrer circle and has its maximum at α equals 60°.) This result is in support of the correctness of curves 1 and 2 and gives confidence that the anomalous shape of curve 2 (for the fiber core) is real. The latter thus reveals that the state of orientation of the core, in contrast to that of the skin, differs from that obtained by the unidirectional stretch of an originally isotropic gel. Other lateral deformations must have occurred which can be associated with effects of lateral shrinkage.

The x-ray results can be interpreted thus: The core substance has been subjected in part to a lengthwise stretch imparting uniaxial orientation, and in part to lateral forces giving rise to a preferred orientation of the A_3 planes perpendicular to the fiber axis (so-called "ring fiber structure"). This is in line with birefringence phenomena as observed on cross sections of rayons with low over-all orientation (*cf.* [4]). As demonstrated by the right-hand part of Figure 16, the lamellar planes A_0 of the crystallites (which always tend to align themselves perpendicular to the direction of shrinkage) have almost the same orientation in both skin and core.

From the differential curves 3 the orientation factors of the skin substance can be computed in the usual way. The values thus obtained are listed in Table VII. Also given is the orientation factor which was found for cord rayon which had been treated in a control experiment with the acid catalyst alone; according to expectation, there was no significant change in orientation.

The results of crystallinity determinations are compiled in Table VIII. I_c represents the integrated intensity of the crystalline peaks; I_m, the height of the maximum of the amorphous background (both expressed in arbitrary units). I_{tot} is the total dif-

TABLE VII. RESULTS OF X-RAY ORIENTATION MEASUREMENTS

Specimen	Amount peeled-off (%)	$\sin^2\alpha_x$	$\sin^2\alpha_z$	$\sin^2\alpha$	f_s
Cord rayon	0	0.0207	0.0507	0.0714	0.89[a]
Cord rayon	20.5	0.0213	0.051	0.0723	0.89[a]
Cord rayon	31.2	0.0212	0.0503	0.0715	0.89[a]
Cord rayon	43.8	0.0235	0.0507	0.0742	0.89
Cord rayon	58.8	0.0203	0.0496	0.0699	0.89[a]
Textile rayon II	0	0.068	0.186	0.254	0.62
Textile rayon II	50	0.070	0.208	0.278	0.58[a]
Textile rayon III	0	0.024	0.059[a]	0.083[a]	0.87[a]
Textile rayon III	58.5	0.034	0.076[a]	0.110[a]	0.83[a]
Textile rayon II skin		0.068	0.111	0.179	0.73
Textile rayon III skin		0.021	0.039	0.060	0.91
Control experiment (Cord rayon treated for 6 days with acid alone)		0.022	0.047	0.069	0.89[a]

* If at a given angle from the equator the intensities on curves 1 and 2 are I_1 and I_2, respectively, and if the peeled-off fraction is x, then the differential intensity for the skin is given by the equation

$$I_s = \frac{1}{x}[I_1 - (1-x)I_2].$$

fracted intensity between $2\theta = 7°$ and $42°$, which should be a constant for all cellulose fibers. It is seen that the crystallinity does not show any significant change with peeling-off. The values are quite near to those normally found for the majority of viscose rayons and indicate about 40% crystalline portion. Perhaps there is a slight increase at the highest degrees of peeling-off, which, however, is an effect of prolonged action of the acid catalyst and is not due to a structural gradient, as corroborated by the control experiment (treatment of the fiber for 6 days with acid alone), where a corresponding small increase was found. It was recently shown [10] that upon acid hydrolysis of regenerated fibers a marked increase in crystallinity occurs. The acid catalyst used in the present experiments may have acted in a similar way.

The photometer curves of the monochromatic exposure of the original cord rayon showed an anomaly, in that the normally existing minimum between the two principal peaks (A_0 and $A_2 + 021 + A_4$) was unusually shallow. This rendered tracing of the background and, consequently, determination of crystallinity very uncertain. For this reason this item is not included in Table VII.

This anomaly has more than once been observed for rayons having a thick skin [8, 9] and seems to be an attribute of the skin substance.* It seems to have been observed also by other authors [11] and was ascribed to the occurrence of cellulose IV.

We have made elaborate efforts to analyze this phenomenon in applying various other techniques of exposure, without as yet reaching any other definite conclusion except that (as we believe to have proved conclusively) the cellulose IV assumption does not hold. It would lead us too far afield to say more about the subject at the present.

Morehead and Sisson [12] also maintain that the skin substance shows a particular x-ray behavior. Although being rather brief on the matter, they claim evidence that the "degree of crystallinity or lateral order" is less in the skin than in the core, and they apparently deduced this evidence from line breadth studies.

Thus far, our own work does not permit us to either confirm or contradict the theory that differences in line width are responsible for the observed anomaly.

* By a special procedure, filaments consisting entirely of "skin" substance, according to the Victoria Blue tests, have been produced in our laboratory. They exhibit the same anomaly in a still greater degree in that the minimum in question entirely disappeared.

TABLE VIII. Crystallinity Determination from X-Ray Data

Specimen	Amount peeled-off (%)	I_{cr}	A_0	I_{am}
Cord rayon	20.5	115	55[a]	440
Cord rayon	31.2	109	55[a]	440
Cord rayon	43.8	117	54	440
Cord rayon	58.8	126	51	430
Textile rayon III	0	110	57	430
Textile rayon III	58.5	114	56	450
Control experiment (Cord rayon treated for 6 days with acid alone)	—	126	51	430

The anomaly in question disappears upon treatment of the fibers in the control experiments with the acid catalyst alone. Fibers thus treated also fail to show a skin-core differentiation in the Victoria Blue test. Obviously, the typical skin structure is destroyed as a result of the action of the acid. Further work is necessary to explain these observations.

Summarizing, the existence of a gradient in orientation, as previously discussed by Preston [13], Wuhrmann [16], Morehead and Sisson [12], and Elöd and Zahn ([1]; *cf.* [14]), is confirmed by the present work.

Shortly after the present work was started, the author had access to an unpublished preliminary report by Prof. O. Kratky on an x-ray investigation (carried out during the war) on the angular width of the A_2-A_4 interference for a German textile rayon which had been peeled-off after Elöd's method. This work of Kratky showed the same effect to exist as has also been confirmed here.

According to a verbal communication by Kratky, several other rayon specimens were also investigated by him at a later date. In this work, the details of which were lost during the war, the same result was obtained in all cases except for Bemberg cuprammonium rayon. For this fiber a reverse effect was found in that the orientation increased towards the core.

Summary

This paper presents a contribution to the knowledge of the inner structure of viscose rayon fibers. The method suggested by Elöd for the layerwise peeling-off of cellulose fibers by acid-catalyzed topo-

chemical acetylation in an indifferent solvent and subsequent removal of the acetylated shell by dissolution was critically re-examined and found to be applicable to viscose rayon. Detailed instructions for carrying out this method are given, and the results of its application in an investigation on the radial gradient of physical properties in some typical specimens of viscose rayon are presented. The fibers investigated were a tire-cord rayon and 3 textile rayons, all of which in the Victoria Blue test exhibited a typical skin-core differentiation.

The course of acetylation and peeling-off was meticulously controlled by dyeing tests applied to cross sections. Relevant micrographs are reproduced. The velocity of acetylation was studied, and it was found that after penetration beyond the skin the velocity of the reaction tends to increase and the attack on the fiber becomes less regular. It is shown that the acid catalyst diffuses into the fiber core beyond the zone of acetylation and may thus cause undesired changes in the physical properties which have to be taken into consideration.

Degrees of peeling-off up to 60% and higher were realized. The physical properties determined were refractive index, birefringence, density as determined from refraction measurements, density as measured by the flotation method, swelling power, and mechanical properties. In addition, orientation and crystallinity as deduced from x-ray exposures were investigated.

In general, Elöd's results were reproduced, with the exception of those regarding density. It was found that as the peeling-off proceeds density and swelling increase and birefringence decreases.

Orientation of the crystalline portion, as computed from x-ray photographs, remained constant in the tire-cord rayon and decreased in the 2 textile rayons investigated. It is shown that the gradient in overall orientation of the latter is due exclusively to changing orientation of the 101 and 002 (A_1 and A_2) planes of the crystallites with respect to the fiber axis, while the orientation of the lamellar 101 (A_3) plane remains constant. No difference in crystallinity between the outer and inner layers of the fibers was found.

No significance can be attached to the observed considerable decreases in tensile strength and elongation since these are the result of the degradation effected by the acid catalyst used in acetylation.

Control experiments in which the fibers were treated with a solution of the acid catalyst in the same solvent, but without acetic anhydride, were carried out in order to examine the possible effect of the acid on any of the physical properties investigated. No effect on orientation was found; density was affected only slightly, if at all. However, in some cases swelling power was considerably changed, although in the opposite sense as in the peeling-off experiments. It is concluded that, in the latter experiments, the observed gradient in orientation and probably also that in density is real, whereas evidence on true differences in swelling power remains somewhat uncertain. The observed increase in density is contrary to the statement in Elöd's paper which claims the reverse effect in fibers of this type. An electron micrograph of a tire-cord rayon is reproduced showing the presence of numerous tiny voids (with diameters from 0.2 micron and smaller) in the skin region. This would seem to explain the increase in density observed for this fiber in areas closer to the core.

It is reported that the skin substance, when examined with x-rays under certain conditions (exposed in the form of isotropic pellets), exhibits a peculiar anomaly as compared to ordinary regenerated cellulose. The true nature of this phenomenon cannot as yet be elucidated.

Acknowledgment

The author is indebted to Prof. O. Kratky for the communications referred to above.

It is the author's pleasant duty to acknowledge the skillful assistance of Miss E. A. Smit, who carried out the tedious experiments with meticulous care.

The x-ray part of this research was performed by Dr. A. Weidinger with the equipment of the Physical Laboratory of the Technical University in Delft.

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TABLE II (EXTENSION)

Specimen	Reaction time (days)	Amount peeled-off (%)	Refractive indices $n_{\parallel}$	$n_{\perp}$	n_{av}	Double refraction $\times 10^3$	Density calc. from n_{av}	Orientation factors Optical (f_o)	X-Ray (f_x)
Cordura	0	0	1.567[6]	1.528[8]	1.541[3]	38.2	1.517	0.76[3]	0.90
Method *C*	3+3+2	62	1.567[4]	1.531[6]	1.543[5]	35.8	1.522[5]	0.71[4]	0.75
Bemberg	0	0	1.567[1]	1.533[2]	1.544[8]	33.8	1.525[5]	0.67[2]	0.86[3]
Method *C*	4+2+1	48	1.571[8]	1.532[5]	1.545[1]	38.8	1.527[5]	0.77[8]	0.87[5]

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(*Manuscript received December 21, 1949.*)

Addendum

After the above paper was already in press, peeling-off experiments on two other rayons were achieved—namely, with Du Pont's tire-cord rayon "Cordura" Type 237, 1100/480, designated as Cordura, and cuprammonium rayon 150/112 from American Bemberg Corp. The results are listed in the extension to Table II.

According to microscopical investigation, the skin was almost entirely removed from the Cordura fibers after peeling-off 62%. It is seen that the orientation decreases and the density increases towards the core, the former effect being surprisingly great in this case.

In the cuprammonium fiber *the orientation effect is reversed* in that the orientation increases towards the core. This is evident from the increased birefringence of the peeled-off fiber.

Curiously, the x-ray orientation factor exhibits but a small (if any) rise. The density gradient shows the same trend as in the previous case.

The material offered in this paper affords further evidence of the fact established in this laboratory that the proportion between the optical and the x-ray orientation factors of rayon fibers is variable in a way which is and for reasons which are still obscure.

Summary

For Cordura tire-cord rayon the orientation decreases, and in Bemberg cuprammonium fiber it increases towards the core.

(*Addendum received January 30, 1950.*)

Studies on the Microbiological Degradation of Wool

Digestion of Normal and Modified Fibrillar Proteins

William H. Stahl, Bernard McQue, Gabriel R. Mandels, and R. G. H. Siu

Contribution of the Quartermaster General Laboratories, Philadelphia, Pennsylvania

Abstract

Measurements of the susceptibility of various keratins and fibrillar proteins to digestion by a keratinolytic fungus were made. Both normal and modified proteins were used. Digestion of the following fibrillar proteins by *Microsporum gypseum* over a 21-day period was, from the highest percentage digestion to the lowest: collagen, feather, hoof, wool, horn, horsehair, mohair, and silk.

The primary factors which determine the rate of digestion of fibrillar proteins were found to be the chemical composition and the molecular architecture. In keratins, the degree of polymerization assumes the greatest importance. The higher the degree of polymerization, primarily attributed to the disulfide cross-linkages, the more resistant the keratin is to enzymic digestion. Histological complexity of keratinaceous tissues and geometrical structure of the keratin molecule do not influence the rate significantly.

Introduction

This study of the digestibility of various fibrillar proteins was undertaken in order to determine whether the relationship, if any, between their chemical and physical structure and their digestibility by the wool-degrading dermatophyte *Microsporum gypseum* might disclose something about the mechanism of the digestion of wool. Three types of fibrillar proteins were used in this study—keratins, collagen, and silk-fibroin. Chemically, the keratins are characterized by their high cystine content and insolubility in dilute acids and alkalies [3, 6, 15]. Adjacent polypeptide chains of keratin are presumably held together by the disulfide linkage of cystine [1, 2]. Collagen is distinguished from keratin by its much lower cystine content and solubility in hot water. Silk-fibroin has no demonstratable sulfur-containing amino acids, has large amounts of glycine and alanine, and is peptized by dilute alkaline solutions or by water under slight pressure.

Several of the substrates used were purposely modified from the normal keratin; the authors do not mean to convey the idea that the conclusions reached *constitute* the mechanism of the degradation of wool. Reduced wool, for example, never appears as an intermediate in the actual microbiological-degradation process. (In a subsequent paper of this series an evaluation of our data in terms of a possible mechanism of the degradation of wool by fungi will be made.)

Experimental Procedure

A. Materials

The sheep-wool used in this study was used as such or was comminuted to various sizes. The following list gives some indication of the substrate particle size:

Range of length of whole wool fiber	= 38–380 mm.
Range of diameter of whole wool fiber	= 20– 40 μ
Range of length of chopped wool fiber	= 30–200 μ
Range of diameter of ball-milled wool particle	= 3– 10 μ

Carefully trimmed and washed pieces of hoof and horn were dried in a vacuum oven at 50° C for 48 hrs., powdered in a hammer mill equipped with a No. 40 sieve, extracted with alcohol and ether, passed through a Wiley mill, and finally sieved to definite particle sizes. The horsehair, mohair, and feathers were washed with water, extracted with alcohol and ether, passed through the Wiley mill, and sieved. The silk-fibroin (China raw silk) was first "degummed" by boiling gently with dilute soap solution, rinsed, and treated as above.

The collagen used was prepared from cowhide which had been dehaired by liming in 4 volumes

of saturated $Ca(OH)_2$, cut into cubes, and washed with acetic acid several times and then with distilled water. Carbon dioxide was bubbled through the final aqueous suspension until the pH was constant at about pH 5. The cubes were dehydrated by acetone extraction at room temperature for 24 hrs., and were then air-dried. The frozen cubes were ground together with dry ice in a Wiley mill.

Amorphous reduced wool was prepared by the method of Goddard and Michaelis [10]. Reduced wool, retaining the physical properties and histological features of normal wool, was prepared by the method of Geiger *et al.* [9]. The oxidized wool was prepared by oxidizing a 5% wool suspension with 5% Superoxol (30% H_2O_2) at room temperature for 18 hrs., followed by thorough washing.

Several samples of woolen cloth * which had been modified by reducing and alkylating, wherein the reactive —S—S— linkage was replaced by an —S—R—S— linkage, were used. These samples were relatively stable to chemical and physical agents [4]. Although an exact, quantitative value of the percent substitution was not available, it appeared to be relatively low. The chemical treatments used were as follows:

Sample	Treatment	Cystine Content† (%)
A	None	11.4
B	Calcium thioglycollate + propylene dibromide (two steps)	8.2
C	Sodium sulfoxylate-HCHO+HCHO (one step)	11.0
D	Sodium hydrosulfite + ethylene dibromide (one step)	8.5

The other chemically modified sample ‡ is known as feather keratin-detergent-complex fiber. This was prepared by reducing keratin at neutral pH in the presence of a detergent of the alkylbenzene-sulfonate type. A compound results wherein the basic groups of the protein unite through salt formation with sulfonate to form electrostatic complexes. Excess detergent was removed, the product was oxidized, and the fibers were produced by extrusion through spinnerets.

Stretched fibers were prepared by placing a combed bundle of approximately 50 fibers (approximately 3 in. in length) between the vertical jaws of stainless-steel clamps with as nearly equal tension as possible on all fibers. A platform, placed beneath, was arranged so that when a weight was attached to the bottom clamp holding the fibers a 100% extension would result. The fibers were then steamed for 3½ hrs., after which they were dried in their stretched state. The portion of fiber between the clamps was clipped to a very short length for use in subsequent experimentation.

B. Digestibility of Normal Fibrillar Proteins

For respective substrates thirty 250-ml. Erlenmeyer flasks, each containing 1.000 g. of the dry material and 80 ml. of nutrient salt solution [20], were used. The substrates, with the exception of collagen, were sterilized in an autoclave for 5 min. at 120°C (15 lbs. pressure). Since collagen is quite readily hydrolyzed by moist heat, a special means of sterilization, which was quite effective, was used. The salt solution, to which a final conc. of 1–1,000,000 crystal violet had been added, was autoclaved separately. At this concentration common contaminating bacteria are inhibited. The dry collagen was heated at 100°C *in vacuo* for 2 hrs. and weighed directly into previously sterilized flasks. The sterile salt solution containing the dye was then added aseptically to the collagen. Two-thirds of the flasks were inoculated with a suspension of *Microsporum gypseum* QM-196 spores. For each digestion period of 3, 6, 10, 14, and 21 days, 2 uninoculated flasks were used for determination of the solubility of the substrate in the salt solution, 2 inoculated flasks for determination of the total residue (mycelium plus undigested wool), and 2 flasks for determination of the mycelium weight.

In determining the percentage digestion, a correction must be made for the residual mycelium weight in inoculated flasks. This weight equals 1.5 times the weight of the residue remaining after 10 min. of boiling in 10% NaOH. Since there is always a small portion of the substrate which is insoluble in boiling NaOH, this value, given in Table I, is subtracted from the above calculated value to give the true mycelium weight. The values for recovery of substrate in uninoculated salt solution, given in Table I, are used in calculating the final percentage digestion.

This correction factor 1.5 was obtained in the following manner: A 4-day growth of *M. gypseum*

* Obtained through the courtesy of Dr. A. E. Brown of the Harris Research Laboratories, Washington, D. C.

† Analysis by authors.

‡ Obtained from the Western Regional Research Laboratory, U.S.D.A., Albany, Calif.

mycelium was thoroughly washed with distilled water and homogenized in a Waring Blendor; total solids present were determined on one-half of the samples; the other half were boiled gently in 10% NaOH for 10 min., thoroughly washed, centrifuged, and the total amount of solids present was determined. An average of 66.5% of the total solids was recovered after boiling in alkali, as determined on quadruplicate samples. Thus the ratio of total mycelium to residual mycelium after boiling in 10% NaOH for 10 min. is 1.5. This factor has a standard error of 0.13.

Digestibility by trypsin (Armour crystalline) was carried out with a 0.05% or a 0.025% solution adjusted to pH 7.5.

Reduced and Alkylated Cloth.—One-half of samples *A* and *D* was used as 1 in. × 3 in. cloth strips and the other half was ground in a Wiley mill equipped with a 40-mesh sieve. All of sample *C* was used as whole-cloth pieces. Portions were reserved as controls, and the main portions were inoculated with *M. gypseum* as previously described. At the end of different time intervals, samples were taken. In the case of the ground samples, the percent digestion of wool was determined, while in the case of the whole strips the breaking strength was obtained on the Scott Tester.

Feather Keratin-Detergent-Complex Protein.—Two types of experiments were set up with this fiber. In one experiment the flasks were inoculated with spores and in the other with an actively growing mycelial mass.

C. pH Studies

Strips of wool charmeen which had been raveled to 3 in. × 1 in. were sterilized by autoclaving for 10 min. after they had been wet in 70% ethanol and rinsed in distilled water. In order to equilibrate the wool with the various solutions that were to be used, the sterile strips were presoaked in sterile nutrient solution at the rate of one strip to each 150 ml. of solution at the pH to be used. Since wool has a fairly high base-exchange capacity, this procedure insured that no significant pH changes would occur due to differential adsorption of ions from the nutrient solutions by the wool. The nutrient solution consisted of the following: NH_4NO_3, 0.0375*M*; $MgSO_4$, 0.009*M*; KH_2PO_4, 0.032*M*; and K_2HPO_4, 0.032*M*. The pH was adjusted by varying the ratio of monobasic to dibasic phosphate. Normal HCl was added in order to obtain the more acid solutions. A second series of cultures was set up with the same solution except for 0.01*M* sodium citrate, which was used as a buffer. (*M. gypseum* does not utilize citrate as a carbon source.)

TABLE I. VALUES NECESSARY FOR CALCULATING THE PERCENTAGE DIGESTION OF THE VARIOUS SUBSTRATES

Substrate	Residue after boiling 1.0000 g. in 10% NaOH for 10 min. (g.)	Recovery from 1.0000 g. of uninoculated substrate in nutrient salt solution* (g.)
Wool	0.0048±.0003†	0.9631±.0156
Mohair	0.0027±.0014	0.9400±.0030
Feather	0.0051±.0002	0.9183±.0090
Horsehair	0.0217±.0065	0.9183±.0049
Hoof	0.0181±.0024	0.9920±.0050
Horn	0.0030±.0003	0.9890±.0090
Silk	0.0310±.0027	0.9996±.0150
Collagen	0.0283±.0035	0.9833±.0098

* Over a 21-day period.
† Standard deviation.

After soaking overnight, two wool strips were placed in each of 6 petri dishes (for each solution, for each of the 3 harvests) containing a layer of sterile glass beads. Ten ml. of nutrient solution was added to each dish, and the strips in 4 dishes were inoculated with a suspension of aseptically washed spores. The remaining 2 dishes served as uninoculated controls. In order to minimize the changes in pH during growth, the solutions in the dishes were changed daily. The old solution was removed by an aspirator, collected, and the pH determined. Fresh solution was then added. Aseptic precautions were observed throughout. At 3, 5, and 7 days, plates were harvested in order to determine the loss in strength of the cloth. The strips were soaked in 70% ethanol for approximately 30 min. to kill the fungus, rinsed, conditioned, and broken on a Scott Tester.

Results

The results of a study of the effect of pH on the degradation of wool cloth strips by *M. gypseum* and their correlation with breaking strength are shown in Figure 1. No significant changes in reaction of the controls occurred. In no case did the pH change exceed 0.25 unit. The optimum pH for the breakdown of wool is between pH 7.0 and 7.5. The acid limit is between pH 3.6 and pH 5.0, excessive changes in reaction preventing a more accurate characteriza-

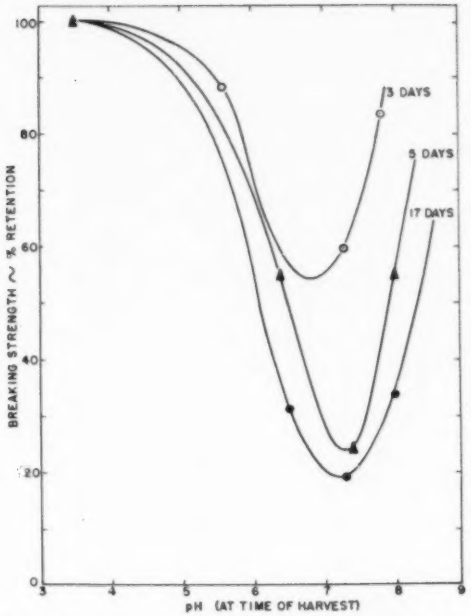

Fig. 1. *Effect of pH on degradation of wool cloth by* M. gypseum *(0.01M citrate buffer).*

tion. The alkaline limit is above pH 8.0. In all cases the solutions became more alkaline in spite of the measures taken to maintain a constant-pH reaction. While many microorganisms possess an adaptive buffering system which tends to change the reaction of the culture solution toward the optimum [7], this mechanism is not operative in the present situation. Citrate at 0.01*M* had little, if any, significant buffering action.

The data for the extent of digestion of the various substrates are plotted in Figure 2. Silk-fibroin showed a small ultimate percent digestion. It was noted that the weight of the mycelium of the 5 samplings of silk-fibroin was approximately one-fifth that of, for example, the mycelium formed on wool. The addition of cystine to the silk-fibroin in the same quantity as that found in wool, or approximately 11% by weight of the substrate, resulted in growth of mycelium and an ultimate percent digestion which was approximately the same as that obtained without added cystine.

The initial pH for all substrates was pH 6.8. It has been observed that the pH at the end of 21 days'

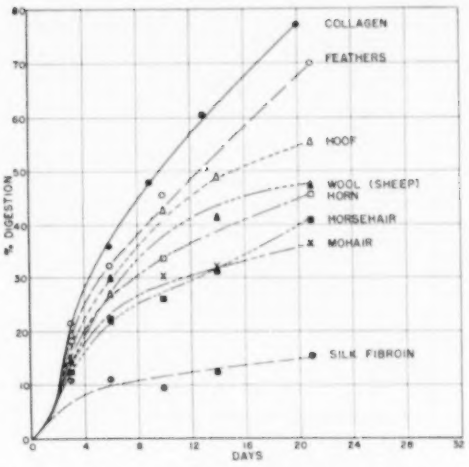

Fig. 2. *Extent of digestion of various substrates by* M. gypseum.

activity of the microorganism was between pH 8.0 and pH 8.6 for all substrates except silk-fibroin, which never went higher than pH 7.0.

No difference in the rate of enzymic digestion between irreversibly stretched and unstretched wool was obtained. Both types in the presence of enzyme * for 7 days showed approximately 20% of the fibers to be denuded or partially denuded of scale cells. Possibly slightly more free cortical cells were noted with the stretched fiber. This may be due to a heat effect [21], such as a decrease in the cystine content, and is not necessarily due to the change from α to β configuration.

Figure 3 presents data [19] from experiments in which wool of different degrees of subdivision were used. The chopped fibers were digested by microorganisms to a greater extent than the whole fibers, and the ball-milled fibers to a greater extent than the chopped fibers.

Chopped fiber is only very slightly digested by trypsin, as indicated in Figure 3. Stoves [22] obtained essentially the same results.

The digestion of normal, oxidized, and reduced wool of different degrees of subdivision, different cystine contents, and different histological structures

* This is the metabolic filtrate resulting from the growth of *M. gypseum* is a mineral salts medium containing chopped wool as the only C and N source. It was grown for 10 days at 30°C.

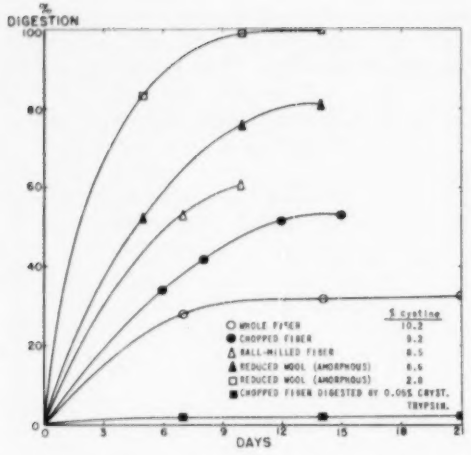

FIG. 3. *Digestion of various forms of wool by M. gypseum or by trypsin.*

is reported in Table II. The photographs in Figure 4 show the initial appearance of some of the wool tested.

Normal whole fiber showed only 0.5% digestion by fungal enzymes. It was noticed that a large proportion of the fibers were denuded or partially denuded of scale cells, and a large number of scale cells and cortical cells were lying about free. This microscopic evidence of degradation is not reflected by the small value of 0.5% digestion.

Normal whole fiber is not significantly digested by fungal enzymes obtained by growing *M. gypseum* on wool or by trypsin, but whole fiber the cystine content of which has been reduced by oxidation to 5% shows definite digestion. Reduced whole fiber shows no digestion.

Comparing the chopped fibers, 3.2% digestion by fungal enzymes for normal chopped fiber was found, whereas for the chopped oxidized fiber, still having all the histological features of normal wool, a value of 17.3% digestion by the fungal enzymes was found. When chopped fiber was highly oxidized so that the cystine content was 2.5%, almost complete digestion resulted.

In all cases, trypsin gave only half as much or less digestion than the fungal enzymes gave. The concentration effect was eliminated by adding excess trypsin in preliminary experiments until equilibrium between digested and undigested wool was reached. Further evidence illustrating the presence of other

TABLE II. DIGESTION OF CERTAIN PHYSICALLY AND CHEMICALLY ALTERED FORMS OF WOOL BY ENZYMES (TIME OF INCUBATION, 4 DAYS)

Substrate	Cystine (%)	Cysteine (%)	Histological structure	Enzyme	Digested (%)
Whole fiber					
Normal	10.13	0	Normal scale structure	Fungal enzyme†	0.5
				Trypsin‡	0.2
Oxidized	5.00	0	Normal scale structure*	Fungal enzyme	11.2
				Trypsin	6.4
Reduced	7.30	1.86	Normal scale structure	Fungal enzyme	0
				Trypsin	0
Chopped fiber					
Normal	10.06	0	Normal scale structure*	Fungal enzyme	3.2
				Trypsin	2.2
Oxidized	2.50	0	Normal scale structure*	Fungal enzyme	96.2
				Trypsin	46.4
Oxidized	6.08	0	Normal scale structure*	Fungal enzyme	17.3
				Trypsin	9.0
Reduced	6.53	2.66	Normal scale structure	Fungal enzyme	3.9
				Trypsin	4.1
Ball-milled fiber	8.60	0.5	Fragmented*	Fungal enzyme	36.5
				Trypsin	17.4
Reduced wool	4.45	—	Amorphous*	Fungal enzyme	97.2
				Trypsin	28.2

* See Figure 4.

† Same fungal enzyme (cell-free filtrate) used throughout this experiment.

‡ 0.025% concentration.

than trypsin-like enzymes in a cell-free metabolic filtrate produced by *M. gypseum* was its further digestive activity on ball-milled wool which had previously been digested twice with crystalline trypsin. Thus, from duplicate flasks containing 0.4000 g. of the crystalline-trypsin digest residue, the data obtained were as follows:

	Amount recovered (g.)	% Digestion
Blank (salt solution)	0.3900	—
Crystalline trypsin (0.05% in salt solution)	0.3900	0
Fungal enzyme filtrate	0.1650	58

Ball-milled wool and amorphous reduced wool (cystine = 4.45%) are essentially similar in particle size, the diameter of the particles being much smaller even than the diameter of a single fiber, as indicated in Figure 4. However, that sample having the lower

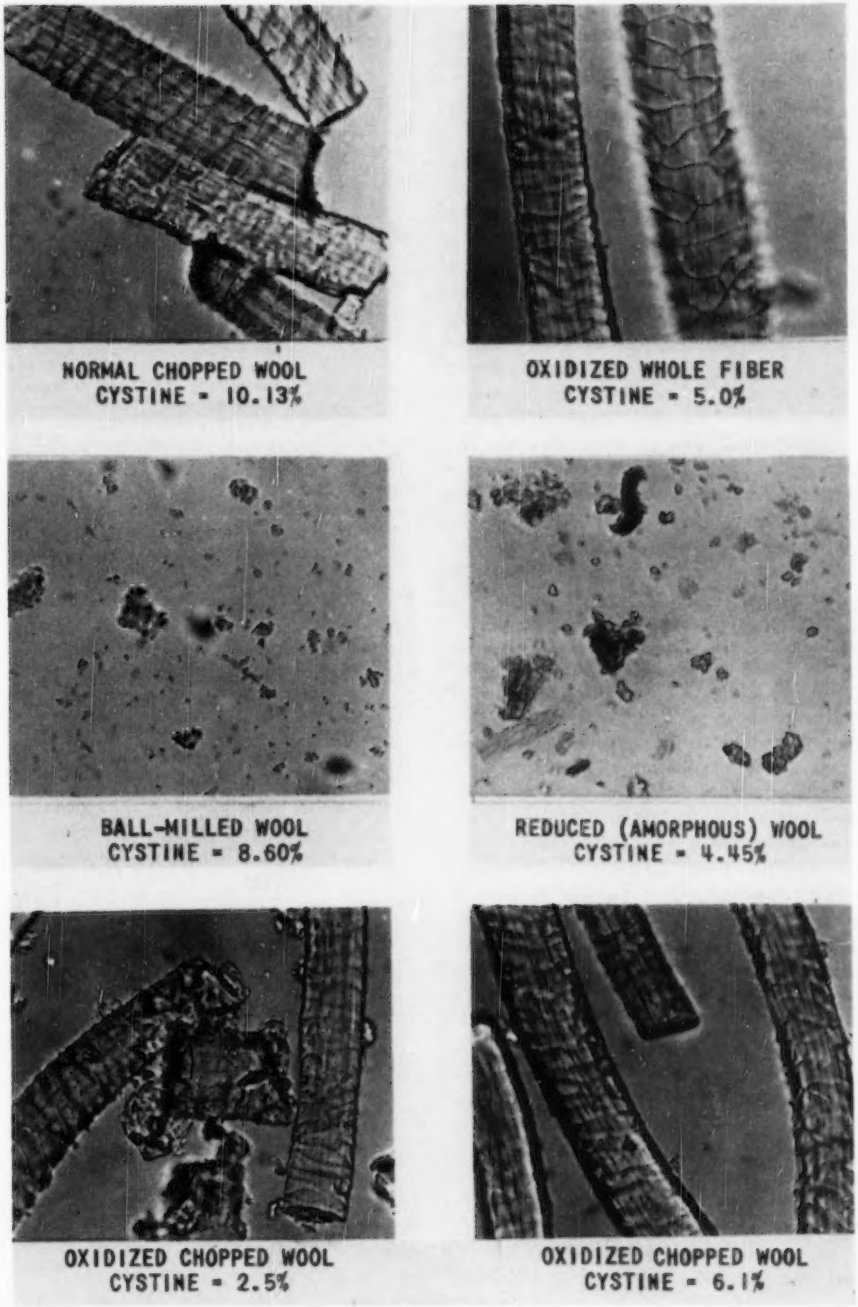

FIG. 4. *Initial appearance of some of the wool tested. Magnification 325 ×.*

cystine content was almost completely digested, whereas that having the higher cystine content (about twice that of the other) was approximately one-third digested.

No digestion of the feather keratin-detergent-complex fiber was noted, when inoculated either with spores or with mature mycelium and incubated for 10 days.

Results on reduced and alkylated cloth are given in Table III. There is only a slight inhibition of digestion of the chopped fiber. In 7 days 41% of the untreated cloth, 25% of *B*, and 32.6% of *D* were digested. This inhibition may be partially due to the incomplete removal of the chemicals used in the treatment of the cloth. The degree of polymerization is not changed by this treatment [4]. However, inoculation of the whole cloth resulted in almost complete loss of tensile strength when there was visible growth on the whole cloth, and in the loss of at least half the original tensile strength when there was no visible growth on the surface of the cloth.

TABLE III. DEGRADATION BY *M. gypseum* OF WOOL MODIFIED BY SUBSTITUTION OF —S—R—S— FOR —S—S—

Sample*	Cystine (%)	*M. gypseum*	Duration (days)	Digestion of chopped fiber (%)	Breaking strength of strips (lb.)
A	11.4	Uninoculated	7	0	50
		Inoculated	7	41	2
B	8.2	Inoculated	3	8.3	
		Inoculated	7	25.0†	
		Inoculated	11	42.5	
		Inoculated	17	61.3	
C	11.0	Uninoculated	21		50
		Inoculated, heavy growth	21		0
		Inoculated, very sparse growth	21		23
D	8.5	Uninoculated	7		41
		Inoculated, heavy growth	7	32.6	5

* For description of treatments see p. 571.
† Estimated from a curve plotted using the other 3 points.

Discussion

A. Rate of Digestion of Fibrillar Proteins by M. gypseum

The term "resistance to digestion" is one which is used very loosely in the classification of proteins. It should be re-emphasized that in contrast to the globular type of proteins which are generally digested by enzyme preparations in a matter of minutes the fibrillar proteins may be comparably digested between the very wide range of from 1 to 10 days. Digestion will take place, but the rate is greatly decreased. Thus, a fibrillar protein is herein considered to be rapidly digested if it is more than 50% digested in not more than 9 days, and very slowly digested if it is less than 20% digested in 21 days. It usually takes 2 days after spore inoculation before mycelium of *M. gypseum* shows visible proliferation, which is counted in the above time.

It is interesting to note the correlation of the digestibility of various keratins by *M. gypseum* and their degree of dispersibility after reduction in neutral solutions of protein denaturants, as reported by Jones and Mecham [11]. In order of decreasing degree of dispersibility, these authors rate the keratins as follows: *chicken feathers*, duck feathers, tortoise scutes, snake skin, *cattle hoof*, *wool*, *cattle horn*, hog hair, human hair, and ovokeratin. The order of this list is in agreement with the present authors' results (the keratins in italics were studied by us). Jones and Mecham point out that reduction of the disulfide groups and alkaline cleavage of secondary linkages are independent reactions, both of which are necessary for dispersion of keratins.

We have been unable to demonstrate that *M. gypseum* releases an extracellular enzyme which is capable of splitting the disulfide linkage of wool. Furthermore, the pH optimum for digestion of wool by *M. gypseum* is that at about neutrality. Possibly there is some relationship between the susceptibility to alkaline cleavage and enzymic digestion. It is not probable that both of the above reactions constitute the initial steps in the microbiological degradation of wool.

While it has been shown that *M. gypseum* produces sulfate during its action on wool [20], it is postulated that this action is intracellular, occurring on absorbed sulfur amino acids or low-molecular-weight peptides.

B. Influence of Amino Acid Composition on Digestibility

It is recognized that the sulfur and cystine contents of keratins vary widely even within one type of keratin—for example, wool. However, it was believed that certain regularities might be shown. One notes that, grossly, the keratins plot as a group (in Figure

TABLE IV. TYPICAL ANALYSES OF FIBRILLAR PROTEINS

Protein	Sulfur (%)	Cystine (%)	Arginine (%)	Tryptophane (%)
Wool[1]	3.6	11.5±0.9	8.4*	1.5*
Mohair[1]	3.1	8.9	8.4	1.5
Horsehair, black[2]	3.6	10.2	8.4	1.5
Cattle horn[1]	2.8–3.6	6.8–8.2	8.4	1.5
Beef hoof[1]	1.8	5.6–5.9	8.4	1.5
Chicken feathers[1]	2.3	6.6	8.4	1.5
Collagen[4]	0.14	0.0	8.8	0.0
Silk-fibroin[3]	0.55	0.0	0.76	0.0

* Mean values for keratins as a group, taken from Block and Bolling.[1]

[1] Block, R. J., and Bolling, D., in "The Amino Acid Composition of Proteins and Foods," Springfield, Ill., C. C. Thomas, 1945, pp. 184–5.

[2] Determined in this laboratory.

[3] Cohn, E. J., and Edsall, J. T., in "Proteins, Amino Acids and Peptides," New York, Reinhold Publishing Corp., 1943, pp. 348, 358.

[4] Bowes, J. H., and Kenton, R. H., *Biochem. J.* **43**, 358 (1948).

2) between the extremes represented by two different fibrillar proteins.

Collagen, silk, and keratins are reported to be resistant to peptic and tryptic digestion. Although all of the substrates studied were three-dimensional polymers, an examination of Table IV shows the striking differences in the sulfur and cystine contents. Other noteworthy differences may be found in the basic amino acid and tryptophane contents.

Silk-fibroin showed a low ultimate percent digestion. It was considered possible that the absence of a sulfur-containing amino acid in silk-fibroin limited the amount of growth and thus limited the degree of digestion. Since upon the addition of cystine no additional digestion ensued, it must be concluded that although a sulfur source is necessary for the metabolism of *M. gypseum* [20] silk has an amino acid sequence in its structure that resists the enzyme-substrate combination, that the amino acid composition per se does not determine ease of digestibility, and that the architecture of the molecule is the critical factor. (The term "molecular architecture" used herein is to be differentiated from "geometrical structure.")

C. Influence of Histological Complexity of Keratinaceous Structures

The fibers investigated differ in their degree of histological complexity. The simpler one-component keratins are horn, hoof, and feathers; wool and mohair are differentiated into two distinct regions—*i.e.*, cuticle and cortex—; and horsehair is the most complex, having in addition to the above regions a medullary region. Data in Figure 2 show no correlation between structure and rate of digestion.

A discussion of the resistance of the cuticle to digestion is given in an article by Mandels, Stahl, and Levinson [14]; similar studies were made by Page [18].

D. Influence of the Geometrical Structure of Wool on Digestibility

Keratins with folded polypeptide chains are designated as α-keratin, whereas those with fully extended polypeptide chains are known as β-keratin. Wool normally occurs in the α form. Since when normal wool was physically altered to the β form and was digested with fungal enzyme no difference between reactions of the two forms could be noted, we make the tentative conclusion that the geometrical configuration of wool, as determined by x-ray analysis, does not influence the rate of enzymic digestion. This conclusion is indirectly supported in reports by Lindley and Phillips [12] and by Carter, Middlebrook, and Phillips [5], who found no difference between stretched and unstretched fibers in chemical reactivity towards sodium bisulfite.

E. Influence of Chemical Modification, Particle Size, and Properties

Geiger and Harris [8] postulated that the resistance of wool to digestion by enzymes is probably due to a unique structure consisting of peptide chains which are joined by disulfide cross-links to form a three-dimensional polymeric network of extremely high molecular weight. The results of this study showed that the disulfide linkage alone is not the rate-determining factor. All the keratins investigated herein have the disulfide linkage and were digested to varying degrees. Collagen, which does not have the disulfide bond, was digested; and silk-fibroin, which does not contain the disulfide bond either, was resistant to digestion.

From the data shown in Figure 3, it would appear that the cystine content is more closely correlated with the rate of digestibility than the particle size is. It may be noted that in the case of the chopped and the ball-milled wool the cystine contents were 9.2% and 8.5%, respectively. However, a calculation of the surface areas of chopped wool and ball-milled

fiber shows approximately a 100-fold increase in area for the ball-milled wool. The increase in activity might be expected to be greater by a factor of 100 if it were proportional to surface area. Actually, the difference is by a factor of less than 2.

While the rate of digestion of wool is unquestionably affected by the particle size of the wool, it must be recognized that ball-milling or otherwise subdividing wool changes its chemical composition [21] as well as increases its surface area. We are primarily interested in the breakdown of normal wool as such and hence are not particularly concerned with the effects of surface area.

The amorphous reduced-wool protein is very readily digested by *M. gypseum*, and the lower the cystine content the greater the ease of digestion, as shown in Figure 3. The difference in cystine content was regulated by the length of time of reduction during preparation. Reduced wool prepared in this manner is an amorphous material and does not have the structure of the original fiber. A comparison of the particle size of this reduced wool (see Figure 4) with that of ball-milled wool would indicate the much greater importance of the comparative cystine contents, since the particle size is essentially the same. The lower the cystine content the greater the ease of digestibility. This is apparently true in the case of the keratins, but is not true of collagen or silk-fibroin.

It is interesting to note that reduced whole fiber, as shown in Table II, showed no digestion. This may be attributed to the fact that the process of reduction [9] was such that a wool fiber containing cysteine resulted. Upon inoculation and shaking in aqueous suspensions, part of the cysteine becomes oxidized, thus re-forming cystine bridges and increasing the degree of polymerization. This was checked by running an uninoculated sample simultaneously and redetermining the cysteine and cystine contents. Also, initially the cystine content is relatively high. Furthermore, if there were any free cysteine this would first have to be converted to cystine, according to the scheme of sulfur metabolism [20], and thus the resistance to digestion of this sample would be further increased. Table II gives data which imply that even when the cystine contents of oxidized fiber and reduced fiber are essentially the same the oxidized fiber is much more readily digested. Goddard and Michaelis [10] claim that reductants do not bring about any other appreciable chemical alteration than that concerned with the sulfur, whereas oxidizing agents are not specific for the disulfide groups but attack the protein molecule at other points also.

Thus, from all of the above data and discussion it would appear that there may be an approximate relationship between the ease of digestibility of the keratins and the number of cystine cross-linkages. Further support for the statement that variation in the nature and number of cross-linkages in the various keratin macromolecules may determine the degree of ultimate digestion is given by Olcott [17], who showed that in the case of hoof protein the residue not digested by enzymes contained more disulfide sulfur than did the original protein. Accordingly, the more rapid enzymic digestion of medullary protein in animal fiber, which has been observed by Stoves [22], may take place in view of the fewer number of cystine linkages in this region of the fiber.

The data of Geiger and Harris [8] support our hypothesis for the ability of the enzymes to digest reduced wool protein in a most satisfactory manner. It was shown by Goddard and Michaelis [10] that reduced wool which had been reoxidized was readily digested by proteolytic enzymes. The so-called "dilution principle" in polymer chemistry indicates that reactions of a low order may be expected in extremely dilute solutions, and higher-order reactions, yielding many-membered polymers, in more concentrated solutions. Geiger applied this principle and showed that when reduced wool fibers are reoxidized, the formation of disulfide cross-linkages is favored because the concentration of reactant is high. Reoxidation by the method of Goddard and Michaelis, in which a dilute solution of reduced wool protein is treated with an oxidizing agent, favored a low degree of polymerization. Geiger then showed that the digestibility was directly proportional to the degree of polymerization, although the proteins were essentially the same in composition.

Further information as to the role of the disulfide cross-linkages and degree of polymerization may be obtained by studying the digestibility of certain derivatives of keratin. The chicken-feather keratin-detergent complex contains not more than half of the original disulfide bonds but has a high degree of polymerization, as shown by Lundgren [13] and Ward *et al.* [23]. However, it was not possible to cause any digestion of this fiber. It is possible that hydrolytic enzymes cannot break down these pep-

tide chains, since the detergent may combine with specific groups which are essential for enzymic reaction and by physical masking or by steric hindrance may prevent the hydrolysis, according to the Bergmann theory of proteolysis. A more likely possibility, according to McMeekin [16], is that the detergent portion of the complex is slightly dissociated, exerting a fungistatic effect. If the latter is the case, no interpretation regarding the mechanism of digestion may be drawn from our data for this compound. McMeekin was unable to obtain digestion of casein-detergent complexes when using pepsin. The possibility of the preparation of textiles from modified proteins such as this one, which is immune to microbiological degradation, should not be overlooked.

Summary

1. The following fibrillar proteins, digested by *M. gypseum* over a 21-day period, may be listed in the following order, going from that with the highest percentage digestion to that with the lowest: collagen, feather, hoof, wool, horn, horsehair, and mohair. Silk either with or without added cystine is only very slightly digested. There is a good correlation between the digestibility of keratins by *M. gypseum* and their degree of dispersibility after reduction in neutral solutions of protein denaturants.

2. The optimum pH for the breakdown of wool by *M. gypseum*, as judged by loss of breaking strength, is between pH 7.0 and 7.5. The acid limit is about pH 3.6 and the alkaline limit is about pH 8.5.

3. The primary factors involved in digestibility of fibrillar proteins were found to be the chemical composition and the molecular architecture. In keratins, the degree of polymerization assumes the greatest importance. The higher the degree of polymerization, primarily attributed to the disulfide cross-linkages, the more resistant is the keratin to digestion.

4. Partial substitution of an alkyl group into the disulfide cross-linkage does not render the fabric immune to attack by microorganisms. Keratin-detergent-complex fiber, however, is resistant to digestion.

5. Preliminary evidence suggests that the proteolytic enzyme mixture produced by *M. gypseum* includes endo- and exoproteinases, other than the type represented by trypsin, which are involved in the degradation of wool.

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INDUSTRIAL SECTION

Dimensional Stability of Woolen and Worsted Fabrics*

Werner von Bergen and Claude S. Clutz

Forstmann Woolen Company, Passaic, New Jersey

IN THE NOVEMBER, 1949, issue of *Wool Science Review*, published by the International Wool Secretariat, Scientific and Technical Department, an article appeared entitled "Cloth Shrinkage in Garment Production" [1]. The introductory statement in this article is as follows:

"Cloth shrinkage is undoubtedly the problem which causes most controversy between the cloth manufacturer and the maker-up. Much of this controversy is due to the lack of technical knowledge of each section of the industry of the processes used by the other. Many of the factors contributing to cloth shrinkage are, however, well established."

This can, without hesitation, also be applied to the conditions in the United States. The amazing thing is that, with all the efforts expended in the last 20 years, this problem is still far from having a satisfactory solution.

Two main types of cloth shrinkage are recognized —the one is known as *relaxation shrinkage* and the other as *felting shrinkage*. The first is regarded as the main factor in the tailoring of a garment, while felting shrinkage is important when considering washable woolen fabrics. A third type of movement in wool fabrics—namely, that caused by *change in relative humidity*—has been found to play an important part in the appearance of lightweight men's suiting, such as the tropical worsteds. This effect was observed especially in suits worn in sections of the country where high humidities prevail—for instance, Florida.

As far back as 1939, studies were made in the Forstmann Woolen Company Laboratories which revealed considerable cloth movement in the warp and filling directions when conditions changed in the range from 20% to 90% relative humidity. When going from the "dry" to the high humidity the cloth stretched, whereas in going from the high to the low humidity the cloth shrank. Depending upon the type of fabric, this cloth movement varied from 2% to 4%.

The solution at that time was thought to be to deliver the goods to the tailor with a moisture content equal to the equilibrium obtained at 60% relative humidity, since at this point the cloth movement in each direction would be only half of the total amount possible. It is interesting to note that a tailoring house recently advertised that it would tailor suits specifically for the various sections of the country in order to give the best-appearing garments.

To find the real causes of this problem, it is necessary to study not only the mill processes but also the steps a piece of cloth goes through during tailoring into a garment.

* Presented at A.S.T.M. Meeting, New York, March 15, 1950.

This paper is appearing also in the July, 1950, issue of the *ASTM Bulletin*.

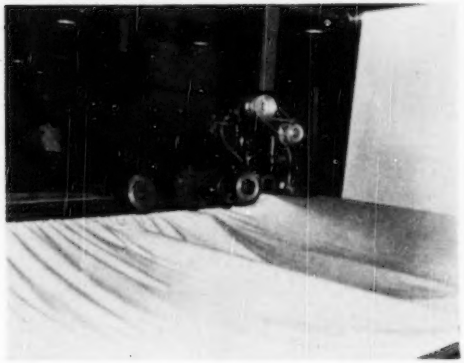
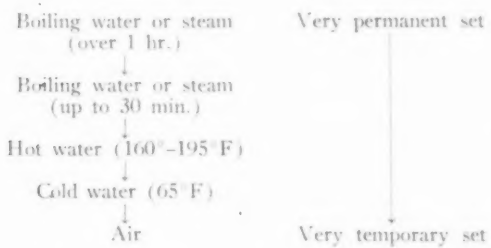


FIG. 1. *Over-feeding mechanism on tenter drier (Krantz). (Courtesy Forstmann Woolen Co.)*

In the article mentioned above [1], the conditions governing the relaxation of stretch are diagrammed as follows:


Boiling water or steam (over 1 hr.)
Boiling water or steam (up to 30 min.)
Hot water (160°–195°F)
Cold water (65°F)
Air
Very permanent set
Very temporary set

It is stated that any setting which has occurred under one of the conditions listed in the diagram can be relaxed by submitting the fabric to any of the conditions above it in the list. If a wool fiber, yarn, or cloth is stretched in dry air, only a very temporary set can be produced. As soon as a fabric so set is brought into contact with water, the stretch will be relaxed.

It is clear that water temperature and time are the important factors in producing set, the permanency of a set increasing as the time and temperature of setting are increased. The fundamentals underlying this conception were first published by Speakman [6].

The findings brought forth in this paper show that the permanent set as produced by the final decating machine in the fabric finishing operations, as well as that produced by the Hoffmann press which is used in the tailoring of garments, can be easily removed by exposing the fabric or garment to high humidity (90% or higher) at normal temperature.

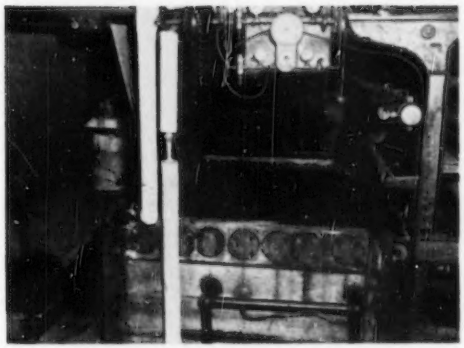


FIG. 2. *London shrinking—wetting-out bath. (Courtesy Forstmann Woolen Co.)*

In Part I of the present paper the writers cover the main processes a piece of cloth is put through in order to reduce relaxation shrinkage to a minimum, and also the main steps this same cloth goes through in a tailoring shop.

Part II contains data and explanations showing how wool fabrics will change in their warp and filling dimensions. These dimensional changes are shown to be attributable to three factors: (1) change in moisture content of the fabric, (2) relaxation shrinkage, and (3) strain due to external stresses. The study includes the action of the Hoffmann press and its use to establish relaxation shrinkage of woolen

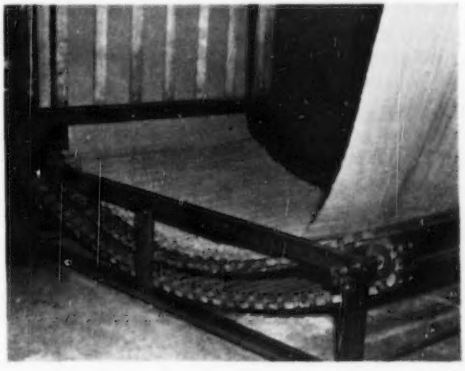


FIG. 3. *London shrinking—relaxation scray. (Courtesy Forstmann Woolen Co.)*

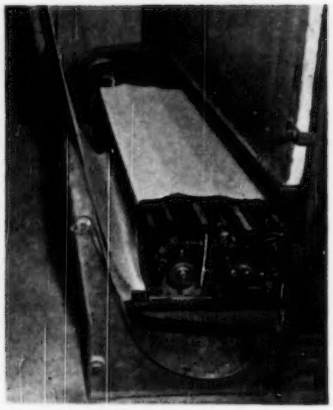


FIG. 4. *London shrinking—drier exit. (Courtesy Forstmann Woolen Co.)*

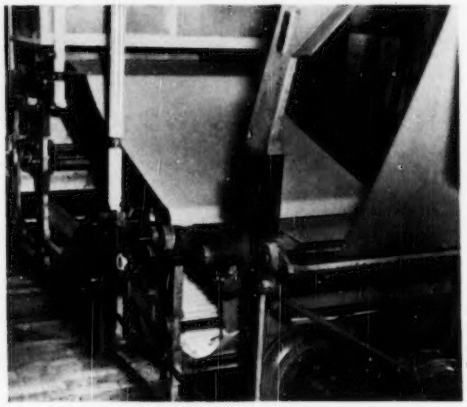


FIG. 5. *Open steaming and cooling. (Courtesy Forstmann Woolen Co.)*

and worsted fabrics. Felting shrinkage is not discussed in this paper.

Part I

Mill Operations

The operations covering the preshrinking of cloth in a mill or sponging house may be divided into two groups—namely, shrinkage by treatment with steam alone, and shrinkage by treatment with cold water.

The modern drying and tentering frames used in the woolen and worsted industry are equipped with electrical feeding mechanisms which allow over-feeding of the material as it enters the drier. Such a mechanism is shown in Figure 1. The cloth in this picture is fed in with an over-feed amounting to 15%, which gives the fabric a chance to fully relax in the warp direction during the drying operation, whereas the shrinkage of the filling is controlled by tentering.

Following the tentering and drying operation, the pieces are subjected to open steaming, cooling, and leader decating, which will be described subsequently.

For cold-water shrinking, in mass-production work, continuous London shrinking machines are used. These consist of three sections—namely, wetting-out bath (Figure 2), relaxation scray (Figure 3), and drier. Figure 4 shows the piece leaving the drying section. As seen from these pictures, the cloth is allowed to shrink freely in the warp as well as in the filling direction.

No matter which method is used—the over-feeding on the drier or the cold-water shrinking—it is necessary to subject the goods coming from the drier to steam treatments in order to remove the folds and wrinkles which were created in the shrinking process. One type of machine is shown in Figure 5. It consists of a steaming unit, a heating or shrinking table, and a cooling apparatus. The cloth enters at the steaming unit, which consists of two steam boxes. From there it slides over the top of the inclined heat-

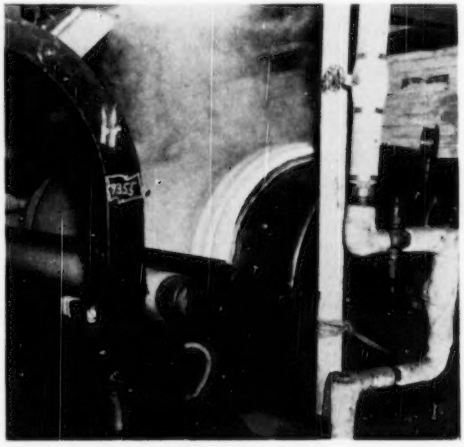


FIG. 6. *Leader decating. (Courtesy Forstmann Woolen Co.)*

Fig. 7. *Layout of pattern and cutting of cloth. (Courtesy Hugh Davis.)*

ing table, falls into a scray where a few yards of the fabric are accumulated, and then passes over a cooling trough which is connected to a powerful suction blower.

For the final setting and smoothing, the fabric is subjected to a steam treatment in a decating machine, as shown in Figure 6. In this machine the cloth is wound with a cotton leader onto a perforated cylinder through which steam is blown. The removal of the steam and the cooling of the piece are accomplished by a suction pump.

In order to maintain the piece in its relaxed position as delivered from the drying units, it is essential that both of the steaming operations be accomplished with the lowest possible tension on the fabric.

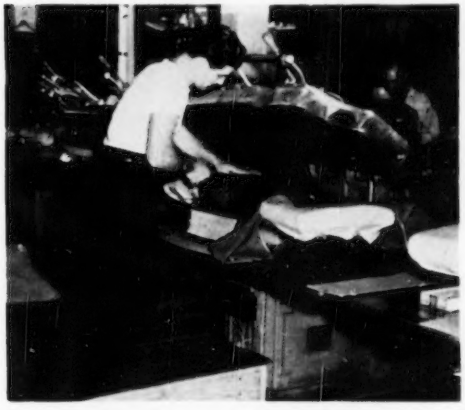


Fig. 8. *Shape pressing of left and right coat fronts. (Courtesy Hugh Davis.)*

Fig. 9. *Collar pressing. (Courtesy Hugh Davis.)*

Steps in Tailoring

There are approximately fifty operations involved in the tailoring of a man's coat. In considering the cloth movement, the main concern is the condition of the cloth as unrolled from the bolt and as subjected to the various steaming operations, either on the Hoffmann press or with the hand iron.

The number of individual pressings which are applied to various parts of the coat is seventeen. These include dart pressing, seam pressing, pocket pressing, collar pressing, etc. Each part is repeatedly pressed between five and seven times, resulting in an average time in pressing of 4 min. During these operations the cloth may be subjected to temperatures from 160°F to 300°F.

In the tailoring house in which the present observations were made, garment manufacturing consists of individual fabric cutting with shears and sectionalized custom tailoring. A suit is made directly to the customer's specifications rather than a standard pattern size.

Figure 7 shows a cutter at work. The necessary amount of cloth has been unrolled from the bolt and the cutter has laid out and traced the left side of the pattern on the double fold of the material. In this

FIG. 10. *Arm-hole pressing.* (*Courtesy Hugh Davis.*)

way, both the left and right sides will be cut simultaneously. Depending upon the amount of time the cloth will lie on the table, there will be a shrinkage or an expansion of the cloth according to the relative humidity conditions—*i.e.*, the change in moisture content of the fabric.

Figure 8 shows the pressing of the entire coat front in a contour press. As the picture indicates, both plates of the press are shaped to the desired form. When the press is closed, steam is applied through the top part of the press for several seconds. The press is kept in the closed position for approximately 30 sec., depending upon the work load of the presser.

Figure 9 illustrates the final pressing of the entire collar. The beds of the press are specially shaped to fit the collar section. Figure 10 shows the last machine-pressing operation, in which the bed-type press is shaped to fit the arm hole. Following this pressing, the coat goes through examining, button sewing, and final hand-pressing with a damp cloth and hand iron, as shown in Figure 11. The final examiner checks all measurements, as seen in Figure 12.

Depending upon the part of the garment (waist or seat), the successive pressing operations shrink the cloth from 0% to 5% according to the state in which the piece was prior to tailoring. Actually, an expansion of the fabric is expected in the waist; whereas in the over-all length and the seat shrinkages of 2% are expected.

FIG. 11. *Final hand-pressing of entire coat.* (*Courtesy Hugh Davis.*)

The condition of the final pressing of the entire garment with a wet cloth establishes the level of the final setting of the garment.

Part II

Change in Moisture Content

The hygroscopicity of wool is well known. This property of wool is one of its greatest assets; however, it is not fully appreciated that it causes appreciable dimensional changes in wool fabrics. The change in the amount of moisture in a fabric with

FIG. 12. *Final examining of coat.* (*Courtesy Hugh Davis.*)

normal changes in weather conditions produces very significant effects in garments. These effects reflect themselves in two ways—change in the size of the tailored garments, and changes in their general appearance.

The literature contains abundant information on the equilibrium moisture content of wool fibers. Considerable data are available on the cross-sectional swelling of wool fibers at various moisture contents; however, the available information on longitudinal swelling is very limited. Brauckhoff [3] gave axial swelling values of 1.7 to 2% between the dry and the saturated conditions for wool fibers, and found this swelling to be independent of fineness and color. In the article by Preston and Nimkar [5] data are listed from the literature on diametric, axial, and volumetric swelling of several textile fibers. Axial swelling for wool is not included in this tabulation. The axial swelling calculated from the diametric swelling of 14.8% to 17% and the volumetric swelling of 36% to 41% would be 3%.

The Foxboro Company, which has had a great deal of experience in the use of hairs in their hygrometer instruments, states that between 20% and 88% relative humidity human hair will change 0.94%. Animal membrane moves 1.9% between 20% and 80% relative humidity [4].

The study of the correlation of the swelling of wool fibers with the motion of wool fabrics with changes in humidity has been neglected. The only reference found in the literature was the article in *Wool Science Review* [1], which indicates a percent area shrinkage of an undescribed fabric when cycled between wet and dry.

Relative-Humidity Motion of Fabrics

The change in the moisture content of fabrics directly affects the change in the dimensions of the fabric. The moisture content of a fabric corresponds to equilibrium at a certain relative humidity. By studying the correlation of the motion with changes of relative humidity, a measure of the fabric's sensitivity to changes in atmospheric conditions is obtained. (The dimensional change of the fabric with changes in relative humidity is termed *R. H. motion* hereafter.)

Test Procedure

In measuring the dimensional changes in fabrics with changes in relative humidity, the fabric is conditioned to a standard atmosphere of 65% R.H. and 70°F. It is then marked in three locations, and brought into equilibrium with 90% R.H. This is done in a special conditioning room, originally conceived by Mr. Henry Booth [2], which measures $12 \times 13 \times 8\frac{1}{2}$ ft. The conditioning equipment is external and is adequate for a temperature range of 40° to 100°F and a relative humidity range of 20% to 90%. Stabilizing to ± 1°F and ± 2% R. H. at any combination of intermediate values within $\frac{1}{2}$ hr. is possible. (See Figure 13.)

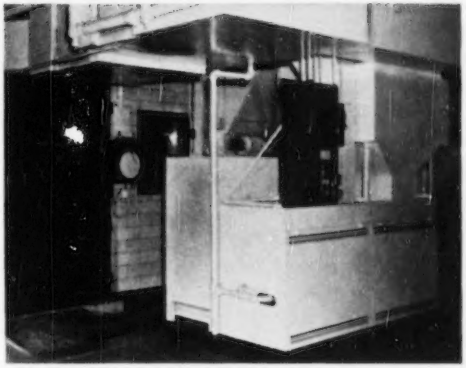


FIG. 13. *Henry Booth special conditioning room.*

After the fabrics are conditioned in this room to 90% R. H., the dimensional change is measured using steel trammels on a beam which has been directly calibrated in percentage change. The fabric is then brought into equilibrium with 20% R. H., which for practical purposes requires not less than 8 hrs. It is measured and again brought to equilibrium with 90% R. H. and remeasured. This completes one cycle; three cycles are run on each sample.

Data

The effect of R. H. cycling is indicated in Figure 14, which shows the change in the warp direction of a gabardine fabric between 20% and 90% R. H. Also included are measurements at intermediate relative humidities.

In Figure 15 similar diagrams are shown for three types of fabric. The flannel and the tropical worsted move nearly the same amount, whereas the gabardine moves to a much greater extent. In general, gabar-

dines move more than other fabrics. This can be attributed primarily to the weave structure and the predominance (in weight) of warp yarn.

Figure 16 shows a combination of R. H. motion and shrinkage tests on a gabardine fabric for 3 swatches laid on a table and measured in the warp direction. One swatch was conditioned to 90%

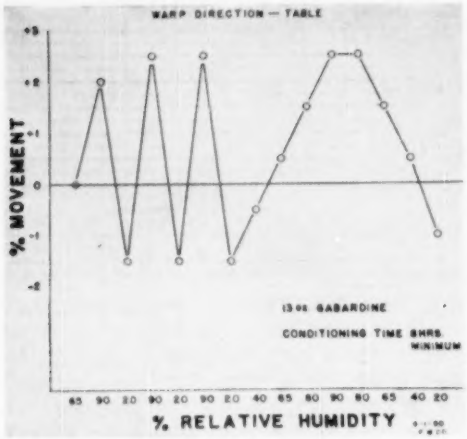


FIG. 14. *Movement of fabric with relative humidity.*

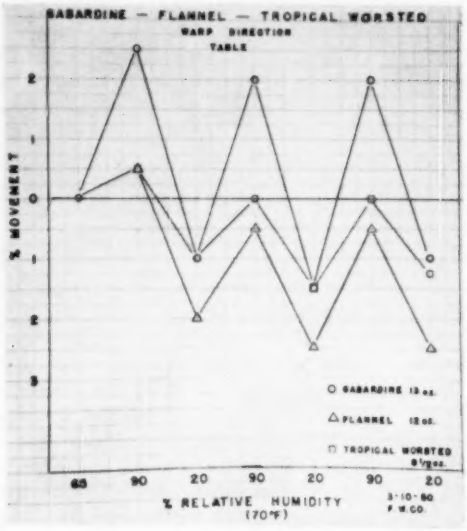


FIG. 15. *Movement of fabrics with relative humidity.*

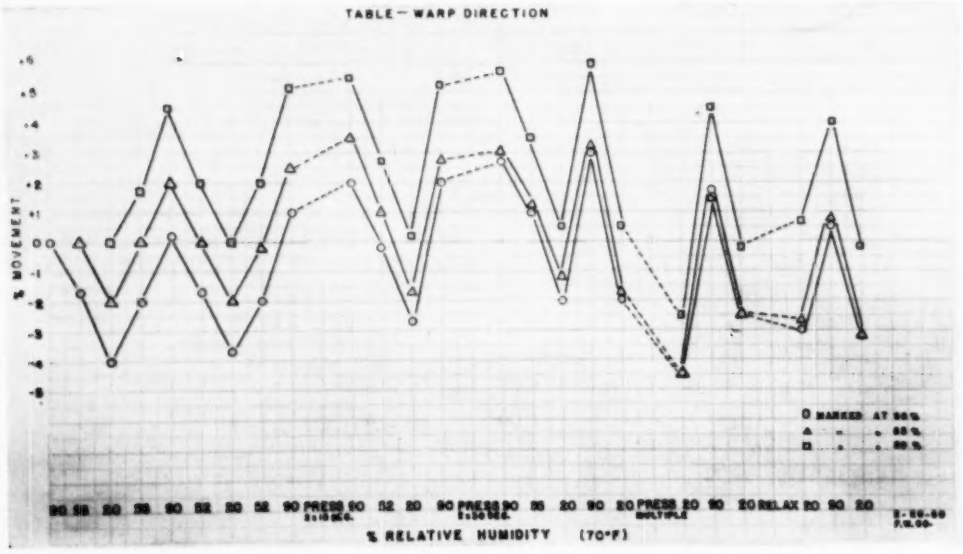


FIG. 16. *Movement of men's-wear gabardine with changes of relative humidity.*

R. H., then marked in 50-in. lengths at 3 locations in the warp direction. The humidity was then lowered to 55%, and a second swatch was conditioned to this R. H. and marked. The second swatch was from the same piece of fabric as the first (see Figure 17). Similarly, a third swatch was marked after conditioning at 20% R. H. These swatches were R. H. cycled and given Hoffmann pressings (indicated by the dotted lines in Figure 16). The pressings are discussed in detail subsequently.

The first pressing operation (Figure 18) consisted of two 15-sec. top and bottom steamings at 65 p.s.i. on a flat-bed Hoffmann press, with a cooling between the two steamings, and the passing of a glass rod under the fabric to aid in relaxation. In this case (Figure 16), no shrinkage was observed when the swatch was remeasured at 90% R. H.; in fact, a slight growth was indicated for all 3 swatches. After the second pressing, which was twice as severe as the first, a slight growth was also observed. The swatch which had initially been marked at 90% R. H. seems to have approached the dimensions of the swatch which had been marked at 55% R. H. In other words, the differences in the dimensions of the fabric had not been maintained. This is believed to be due to the restriction of motion which resulted from the fact that the swatches were lying on the table.

The third shrinkage test consisted of successive pressing operations of 30-sec. each, terminating when

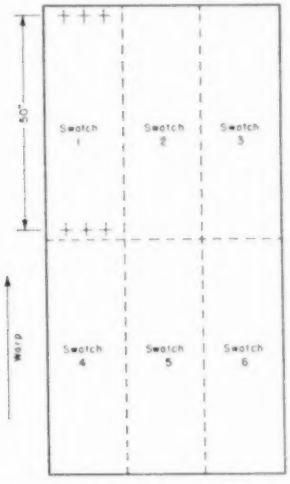


FIG. 17. *Swatch layout from piece of fabric.*

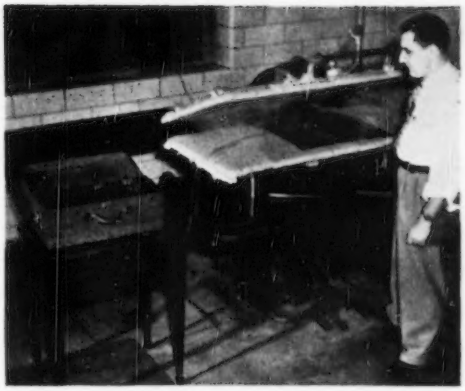


FIG. 18. *Steam test showing Hoffmann press and testing instrument for temperature.*

the fabric moved no more. This required 6 pressings on the average, and an apparent shrinkage of 3% was obtained. It is to be noted, however, that after the swatches had been put through an R. H. cycle practically all of the apparent shrinkage had been removed. The indicated shrinkage was reduced to less than 1%.

The last test on these fabrics was a relaxation test consisting of saturating the fabric in water at 80° to 90°F and allowing it to drain and condition on a table. In this case, there were small inconsistencies but no shrinkage was indicated (Figure 16). After the fabrics had gone through an additional R. H. cycle, the measurements were essentially the same as before relaxing.

Figure 19 gives similar data except for the fact that the swatches were suspended from a wire rather than laid on a table. These swatches were cut from the same piece of fabric as shown in Figure 17. With this procedure, better consistency of results was obtained, particularly for the relaxation tests. The actual motion between 20% and 90% R. H. was greater than when the fabric was on the table. Again, the first two steam pressings show no shrinkage. For multiple steam pressing 3% shrinkage is indicated, but R. H. cycling through 90% R. H. removed practically all of this apparent shrinkage; therefore, this was not a true shrinkage because if it were it would have been permanent to R. H. motion. On relaxation, however, some shrinkage was obtained on these swatches. This shrinkage was re-

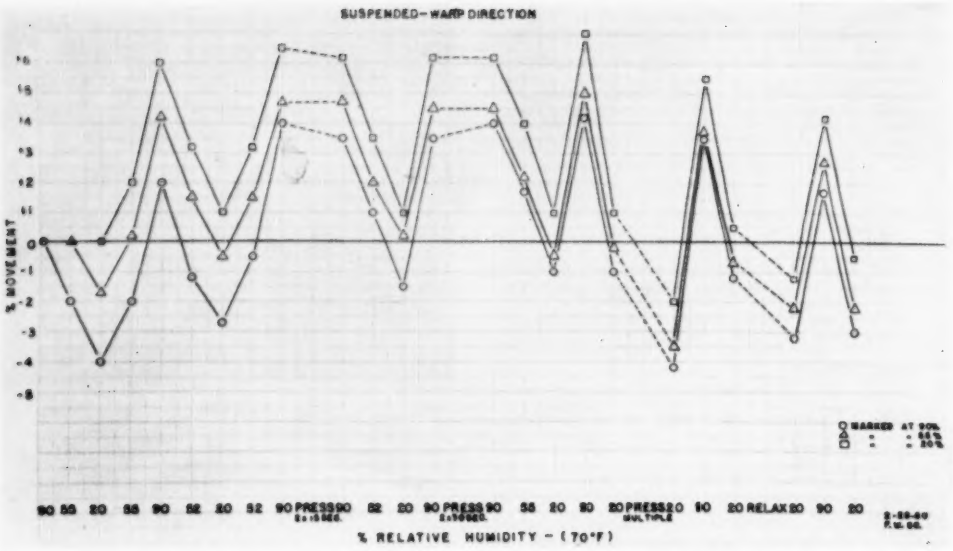


FIG. 19. *Movement of men's-wear gabardine with changes of relative humidity.*

tained after a cycle through 90% R. H. and therefore must be significant; since no relaxation shrinkage was obtained on the swatches on the table, this was due to the strains imposed by the weight of the fabric during suspension.

In Figure 20 details are given of the steam-test shrinkage on the swatches shown in Figure 16. The graph on the upper left-hand side shows the change in dimension of the swatch measured at 90% R. H., then at the press after the pressing operation, and again after it was reconditioned to 90% R. H. This swatch was originally marked at 90% R. H. and showed an apparent shrinkage of 4% when measured at the press. Of course, this is not a true shrinkage because when it was returned to its original moisture content the shrinkage was removed. The swatch which had been marked at 55% R. H. showed an apparent shrinkage of 1.7% even after reconditioning to its original R. H. The third swatch (marked at 20% R. H.) showed a shrinkage of 1%.

The second series of steam tests recorded in Figure 20 was the same as the first except that the steaming time was increased to 30 sec. This more severe steam-pressing test showed no fabric shrinkage when the test swatch was reconditioned to its original humidity after going through 90% R. H.

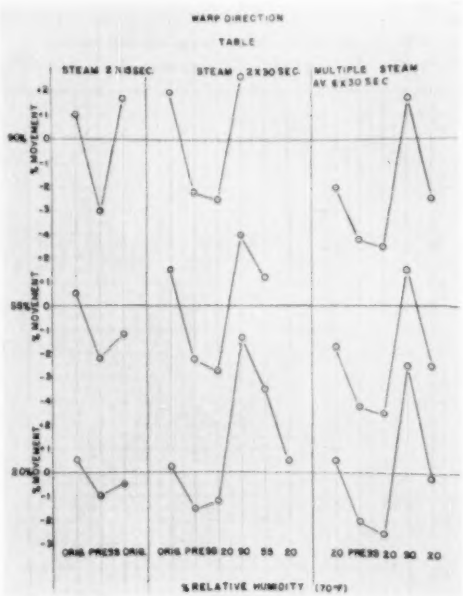


FIG. 20. *Influence of steam pressing on men's-wear 12-oz. gabardine.*

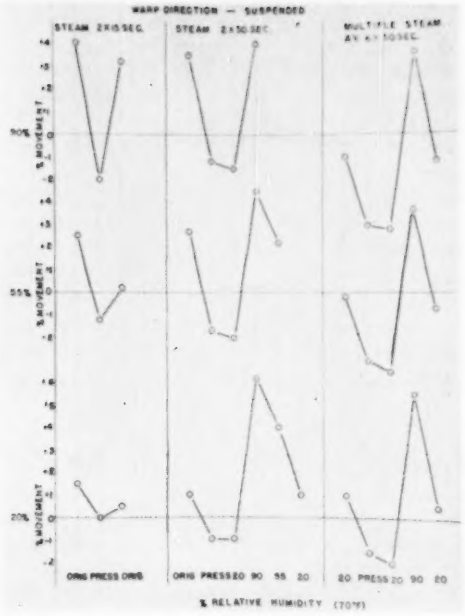


FIG. 21. *Influence of steam pressing on men's-wear 12-oz. gabardine.*

In the third pressing-test series, the fabric was pressed until equilibrium was reached at the press. The motion from this test was entirely removed when the specimens were put through a R. H. cycle.

In Figure 21 information is given on the swatches which were suspended. The total movement for the swatch which had been marked at 90% R. H. and measured at the press was 6%. Upon being returned to its original condition of 90% R. H., the shrinkage indicated was only 0.7%. These tests show that nearly all of the steam-pressing movement can be removed by cycling through 90% R. H.

In Figure 22 data on the relaxation test are graphed. The swatches which were placed on a table show no significant shrinkage; however, all 3 of the suspended swatches shrank approximately 1.5%, which shrinkage was retained when the swatches were conditioned through 90% R. H. This indicates that strains existed in the fabric which were due to the weight of the fabric during the numerous hours of cycling. The average shrinkages of the

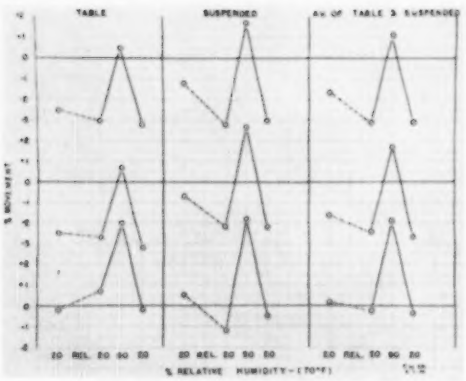


FIG. 22. *Relaxation test data for 12-oz. gabardine.*

swatches on the table and those suspended are graphed in the third section of Figure 22.

Table I summarizes the data shown in the graphs and also includes the moisture regains at the various relative humidities.

It can be seen that the average motion of this particular gabardine (on table) from 20% to 90% R. H. was 4.4%, but when the specimens were suspended it was 5.7%. The greater motion of the suspended samples compared to that of those on the table may be due to either the weight of the fabric when it is suspended or the restriction in motion when it is on the table. The hysteresis effect indicated shows the difference in the dimension of the warp between desorption and sorption at 55% R. H. The corresponding moisture regain of these fabrics was 11.7% on desorption and 10.9% on sorption. This difference of 0.8% is somewhat lower than the 2% shown by Weigerink [7] in this region. The fabric regains shown are about 2% lower than the

TABLE I. EFFECT OF HUMIDITY ON MOTION AND MOISTURE REGAIN OF 12-OZ. GABARDINE AT 70°F

	R. H. motion	
	20%–90% R.H.	55% R.H. Diff. Des.-Sorp.
Av. motion—Table	4.4%	0.5%
Av. motion—Suspended	5.7%	0.7%

Moisture regain

Relative humidity	Regain
20%	5.8%
90%	19.1%
55%, desorption	11.7%
55%, sorption	10.9%

FIG. 23. *Freshly pressed coat at 20% relative humidity.*

FIG. 24. *Same coat as in Figure 23 at 90% relative humidity.*

corresponding values given by Weigerink for clothing wool. It is normal for fabrics to have these lower regains.

Additional test data are shown in Table II. These tests were made on 4 swatches (2 for test A, and 2 for test B) which had not previously been R. H. cycled. The effect of successive relaxation and Hoffmann steam-pressing tests is illustrated in this table. Results shown are the averages of 3 measurements taken on each of the 2 swatches.

Test procedure A shows a fabric shrinkage of 7.2% after the second relaxation. Due to the high amount of relaxation shrinkage, the full shrinkage was obtained only after the second water treatment. An additional 1% shrinkage was obtained with 2 Hoffmann pressings (steps 3 and 4). This shrinkage, however, was not retained when followed by steps 5 and 6. The shrinkage obtained in step 6 was identical with that in step 2; therefore, it can be considered as the normal relaxed condition of the fabric. This is further substantiated by R. H. cycling the fabric (step 7) and relaxing again (step 8).

In test procedure B, 2 Hoffmann pressings (steps 1 and 2) produced an initial shrinkage of 3%. When followed by water relaxation (steps 3 and 4), the shrinkage increased to 7.1%, which is nearly identical with the shrinkage obtained in step 2 of test A. Two Hoffmann pressings (steps 5 and 6) brought a further increase in shrinkage amounting to an additional 1.4%, but this was completely removed in steps 7 and 8. The relaxed condition obtained in step 8 is equal to that in step 4 as well as to the condition established in steps 2, 6, and 8 in test procedure A.

These data conclusively prove that Hoffmann pressing cannot be used to measure fabric shrinkage. On the other hand, water relaxation gives an accurate and reproducible measure of the fabric's normal state. It further shows that any setting action produced by Hoffmann pressing does not alter the relaxation test results.

TABLE II. SUCCESSIVE PRESSING AND RELAXATION TESTS: PERCENT DECREASE IN WARP FROM ORIGINAL 12-OZ. GABARDINE CONDITIONED TO 65% R. H.

Step	Test A		Test B	
1	Relaxed	5.7	Pressed	2.2
2	Relaxed	7.2	Pressed	3.0
3	Pressed	8.2	Relaxed	7.0
4	Pressed	8.2	Relaxed	7.1
5	Relaxed	7.5	Pressed	7.6
6	Relaxed	7.2	Pressed	8.5
7	R. H. cycled	7.6	R. H. cycled	7.0
8	Relaxed	7.1	Relaxed	7.1

Figure 23 shows the appearance of a freshly pressed man's gabardine suit coat at 20% R. H. The same coat after exposure to 90% R. H. is shown in Figure 24. The dimensional change is not obvious but the appearance change is. The R. H. motion of the fabric has been restricted by the component parts of the garment such as seams and tapes. The fabric cannot increase in length and takes the other alternative by growing in the third dimension, producing the apparent irregularities of puckering and bubbling at the lapels, pockets, seams, and edges. This shows the effect of fabric R. H. motion on garments when motion is restricted. The over-shrinkage in Hoffmann pressing, which is removed at high humidity, further accentuates these irregularities.

Summary and Conclusions

It has been shown that changes in the moisture content of wool fabrics cause dimensional changes in those fabrics. By studying fabric structures and the susceptibility of fabrics to R. H. motion, indications of the changes in dimensions and in garment appearance which may be encountered at high humidity in tailoring garments are obtained. In addition, the study of R .H. motion in conjunction with steam-test shrinkages emphasizes the inaccuracy of shrinkage test procedures. It was shown that steam-test shrinkage of a fabric may give a false indication. First, it is essential that the fabric be reconditioned to its initial moisture content when making shrinkage tests in order to avoid including any R. H. motion in the shrinkage test. Secondly, it was shown that the steam press may overshrink a fabric—in other words, produce a shrinkage beyond the relaxation shrinkage which is not stable to R. H. cycling—and, therefore, does not provide a true test. Since steam-test results are not reproducible, they cannot be used as a true indication of the shrinkage of the fabric. Rather, steam-test shrinkage results crudely combine R. H. motion and a partial relaxation, with the introduction of temporary strains.

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Wool as an Apparel Fiber

Giles E. Hopkins*

The author of this paper, admittedly interested in the utilization of wool, has made a study of present scientific and technical knowledge concerning the functional requirements of clothing and the properties of textile fibers. He discusses some of the principal factors governing fiber and fabric relationships as they relate to the requirements of apparel fabrics, such as bodily comfort and protection as well as appearance and style. The paper should be of value to all persons who are interested in the development of improved apparel textiles irrespective of their interest in particular types of fibers.—Editor

Introduction

The superior qualities of wool as an apparel fabric have been accepted as a traditional concept. This acceptance has been based on experience through the generations without explicit analysis—even before it was possible to measure many of the basic properties which made wool so eminently satisfactory.

As facilities for testing fiber and fabric characteristics have been developed, the results of these tests have been distributed through the literature. Until recently there has been little attempt to analyze the relationships between the properties of the fiber and those of the final garment into which it is fashioned, or to codify the measurable garment characteristics.

As a matter of fact, it might be stated that the stimulus to the present rapid advances in the extension of our fundamental knowledge and the anticipated application of this knowledge to the improvement of functional properties of apparel fabrics have resulted to a large degree from: (1) the brilliant work of Harold DeWitt Smith [13] in advocating an engineering approach to the evaluation and utilization of textile fibers and in reducing the available test data to engineering terms; and (2) the exhaustive U. S. Army investigations of the physiological demands on clothing under extreme conditions of exposure.

The scientific analysis of clothing demands for the military and the associated influence on sports clothes have been especially significant. They served to emphasize the functional properties as differentiated from style, appearance, and the other areas of "wantableness" which lie more in the psychological than in the physical field. The appeals stemming from tradition, pride, and ambition are strong influences in the selection of civilian apparel. But even in this area of intangibles there are some features, such as maintenance of fit, resistance to crushing, softness to the hand, and warmth to the touch, which can be associated with measurable qualities.

Of necessity this discussion must be confined to those areas where a correlation between "wantableness" and measurable characteristics can be developed. It is significant to note that many of the preferences which stem from tradition and habit may give way to functional values when the latter have been demonstrated. As an illustration, cold-weather sports clothes which were loose at the cuffs, ankles, neck, and waist have given way to garments with tightly fitted closures. It is reasonable to suppose that in time this willingness to modify traditional ideas, "for cause," may be extended to other types of clothing, especially work clothes or clothes for which performance is important.

In this article we will first analyze the desired qualities of apparel fabrics and point out the specific fiber properties involved. We will then compare these properties in the common fibers which are commercially available.

* Technical Director, The Wool Bureau, Inc., 16 West 46th Street, New York 19, New York.

Criteria of Value in Apparel

The various factors which may be considered to influence acceptance of an apparel fabric can be divided roughly into four main categories: appearance, touch reaction, maintenance and serviceability, and protection. The relative importance of these individual factors varies, of course, with the type of garment and its field of use. These differences will be discussed later.

Appearance

The appearance of a fabric is, of course, especially important in garments used for dress or business; it is important in nearly all nonfunctional women's wear, and, to a strong degree, in functional sports-wear, especially of the type worn for sports enjoyed jointly by both sexes.

Appearance may be classified according to such qualities as color and texture, drape, luster, and fit.

Color and texture may be largely controlled by the selection of manufacturing methods and design. Wool dyes to rich, deep shades. The association of wool with winter wear and men's clothing has called for the darker or "muted" colors. The use of light-weight tropical suitings, the large increase in the use of sheer worsted dresses by women, and the popularity of dry-cleaning and high styling have served to introduce light, bright, clear colors. The materials and techniques to provide these bright colors with the desired fastness are available. Wool therefore is almost without limitation in color quality.

The influence of women's styles and convenient dry-cleaning, recently supplemented by shrink-resistant treatments for sports-wear and other articles which require frequent cleaning, has placed emphasis on clean, smooth textures. These are readily available in worsteds, gabardines, meltons, jerseys, serges, and the like. The felting qualities, which are exclusive to wool and certain other fur fibers, are important in creating many of the finishes which are so desirable. Where rough surfaces are desired, the hairy, resilient qualities of wool are important.

Drape is a quality which is difficult to measure. The concept of drape probably includes the joint influence of visual and touch reactions. Without doubt luster is involved; certainly pliability, resilience, lack of sleaziness, and even smoothness or hairiness of surface are involved in the evaluation of drape. Research now in progress may give us a greater understanding of the degree to which flexibility (in bending), extensibility (in elongation), firmness of weave, luster, etc., influence the drape value of a fabric.

Luster depends on the amount and pattern of light reflected from the fabric. It is a difficult characteristic to measure in its eye appeal. The most lustrous fibers create an unpleasant metallic "shine." Wool has a characteristic rich luster which is especially associated with high quality and softness (as a visual reaction).

Within limits, the luster of wool can be controlled. It can be increased chemically, as by chlorination, and it can be controlled in the fabric, as by the type of finish and the weave selected.

Fit refers to the molding of the garment to the individual. It probably includes some degree of drape. Fit is that quality which indicates that the garment was made specifically for the wearer. It is controlled in gross adjustments by the design and cut of the material. But no amount of careful measuring and cutting will make a stiff, boardy material give complete satisfaction in fit.

The felting properties of wool are important aids in obtaining exact fit. After perfect tailoring the last little adjustments are made by "shrinking" local areas in order to improve the set of the collar or the hang between the shoulders. Flexibility, elasticity, and elastic recovery are important in securing fit.

Hand or Touch

Aside from the visual characteristics, the desirability of fabrics is also influenced by the "hand," or the appeal to the sense of touch. Firmness, resilience, and softness are involved. It has also been suggested that warmth or heat conductivity may be included. In addition to its dependence on the fabric design or construction used, the hand of wool fabrics depends also on the flexibility, toughness, elastic recovery, mass compressibility, mass resilience, and specific volume of the wool fiber.

The warmth to touch involves the heat conductivity of the fiber and the amount of fabric area in contact with the skin. The conductivities of the various fibers are not significantly different. However, the slick fibers, such as nylon, rayon, and cotton, give smooth, cool surfaces as compared with the hairy, warm surface of wool. As pointed out by Fourt and Harris [10], wool is the hairiest of the fibers; and because of its hairiness the area which

comes in contact with the skin is so small a part of the gross area of the fabric that it feels warm because the body heat is not taken away by conduction.

Under conditions of actual service, the touch qualities of a fabric are very much affected by fabric moisture absorption. Damp fabric in contact with the skin feels cold and clammy. The hairiness of wool reduces the clammy feeling by reducing the area of fabric in contact with the skin.. In addition, the natural absorbency of wool makes it possible for the wool fabric to soak up as much as 30% of its own weight in moisture without feeling wet.

Maintenance and Serviceability

Relative ease of maintenance and length of service are important in work clothes, business clothes, and those items of dress and sports-wear which are not subject to frequent style changes.

There is a tendency to oversimplify the wear evaluation of apparel by the exclusive use of abrasion-testing. Even when the wear-life of a garment is defined as its service to the point of physical destruction, abrasion represents only one form of wear. Garments are also destroyed by tearing and snagging. They are made unusable by the development of ugly shine, stretching out of shape, shrinking, staining, or just going out of style. The relative importance of these several factors varies widely with the type of garment, the type of service, the social position or ambitions of the wearer, and innumerable other considerations. The many possible variations in the distribution of these factors cannot be covered in a general article of this type. The good wearing qualities of woolen and worsted garments are generally accepted. We need to know more about the interrelationship of fabric design and service.

Maintenance of Press.—Most wool fabrics are pressed to give a desired hang and contour. The "set" taken by wool when it is damp and hot is one of its valued characteristics. Cotton also can be pressed, but cottons and rayons are more easily crushed and wrinkled. Special treatments applied to these fabrics to reduce crushability make pressing more difficult in direct proportion to their effectiveness in achieving crush-resistance.

Wool has the ability to take a press, combined with crush-resistance. Casual wrinkles, such as those caused by sitting, come out almost as soon as the wearer changes his position. More permanent wrinkles which are partially set in the fabric by moisture from the body, from long packing, or from wearing in the rain will usually come out on hanging. As a matter of fact, the addition of wool to rayon and cotton in blends will frequently improve their crush-resistance more effectively than it is possible to do by the use of crush-resistant chemical treatments, and the wool will also improve the pressing qualities of the fabric.

The crush-resistance of wool is largely dependent on its elastic recovery and its resilience.

Ability to Maintain Shape.—When a garment is worn, small areas are exposed to localized strains. Pockets stuffed with papers, compressions at the front of the shoulders, tensions at the knees, all induce repeated and sometimes continuous stresses which tend to distort the desired hang or shape of a garment. Wool is an elastic fiber, which allows these distortions without interfering with body movement, but both its elastic recovery and its resilience after compression greatly assist the garment to return to its original contours. Its plasticity under heat and moisture and its ability to shrink also assist in bringing wool garments back to the desired dimensions on pressing.

Cleanability.—Wool and worsted garments can be dry-cleaned without loss of shape and fit. Certain types of wool fabrics are now given shrink-resistant treatments and hence may be washed. Shrink-resistant treatments are applied most frequently to those garments which are most subject to soil and which must be frequently laundered. Suits and coats which have padding and fittings which will not stand washing are, of course, not commonly shrinkproofed.

Protection

In hot, humid environments clothes may be an actual impediment to the body's natural heat-regulative processes, but they do afford protection against insects and some body injuries. In contrast, clothes are important aids to body temperature regulation in hot, dry countries, particularly in direct sunlight. In all cool climates clothes are of course a distinct aid in maintaining bodily comfort and even life. Recently published reports give considerable information on the body heat-regulation mechanism [9, 21].

The body gains heat from the environment by conduction, convection, radiation, and evaporation. It has the necessary facilities for effecting a balance between the heat gained and lost to the environment and that created by metabolism in order that the

temperature of the vital organs in the trunk shall be kept approximately constant. If the internal temperature rises or drops more than a few degrees, death results. The body fights to maintain a constant internal temperature. It even has facilities to cut off circulation to the extremities, abandoning them if necessary, so that the vital functions may be protected.

Bodily Adjustments under Hot and Cold Conditions [9, 21]

Cold Environment

If the body loses heat to the environment too rapidly the circulation of the blood is withdrawn from the surface. This greatly reduces the blood-cooling effect (which resembles that of the circulation of water in an automobile radiator), which takes place when the blood flows freely close to the surface of the skin. It also reduces the amount of tissue to be maintained at normal temperature. The top centimeter of body tissue makes up 21% of the total weight of an average man. The top 2.5 centimeters makes up half of his weight.

This cutting off of surface circulation causes a drop in skin temperature, and this, in turn, reduces heat losses from the skin to its surroundings, since heat losses through conduction, convection, and radiation are all directly proportional to the temperature differences between the skin and its environment.

Since the insulation value of the surface tissue is greatly increased under conditions of reduced surface circulation, this reduction in surface circulation serves to conserve the heat in the internal organs, reducing conduction of heat to the skin.

There is then an urge for activity and shivering takes place, both of which increase the rate of metabolism and thus speed up the production of heat in the body.

Later in the course of exposure to cold conditions, the individual makes other involuntary adjustments. He tends to assume a crouched or hunched position, thus reducing the body area exposed to the surroundings. His arms are brought in across the chest. The legs are drawn up to the belly and held close together. Goose pimples appear and the hair on the body stands straight, thus increasing the thickness of the insulating layer of air next to the skin, or reducing the erosion effect of air movement.

Under extreme conditions the circulation to the extremities is cut off.

Hot Environments

In hot environments the blood circulates next to the surface of the skin. Skin temperatures all over the body approach the internal body temperature. This gives maximum cooling of the blood, utilizes the maximum area for such cooling, increases body heat loss by increasing the temperature difference between the skin and its surroundings, and the insulating value of the surface tissues is reduced.

Sweating takes place, and the evaporation of this water on or near the skin has extensive cooling effect. Under high heat conditions a man can evaporate 2 to 3 pounds of water per hour.

The individual tends to become inactive. At rest he lies in a spread-eagle position in order to give maximum evaporation area.

Sweating increases with the organism's demand for cooling. After prolonged exposure, however, sweating is decreased to prevent dangerous dehydration. The sweat rate of an unacclimatized man decreases 10% to 80% in 6 hours. Farmers and laborers guard against this dropping off of the sweat rate by wearing long woolen underwear when working in the heat. Sweat that might otherwise have run down into their shoes is stored up in the wool and is then available for evaporation after their own sweat production has been reduced.

The Function of Clothing in Heat Regulation [10]

Clothing may assist body temperature regulation by cutting down the body heat gains and increasing the body heat losses in hot environments and by cutting down the body heat losses in cold environments. It can also create inertia effects which prevent sudden chilling due to too rapid an evaporation of accumulated sweat after activity ceases. The absorptive quality of wool increases this inertia effect.

Conduction

Conduction is the direct transfer of thermal energy through solids, gases, or liquids. The conductivity of air is extremely low. The conductivity of water is high. There is little difference between the actual

conductivities of the various textile fibers themselves. In most fabric constructions encountered in warm apparel the actual fiber makes up not more than 20% of the total fabric volume [19]. Hence the controlling factor of conductivity is the entrapped air. As Schiefer [12] has shown, among common fabrics the conductivity is roughly proportional to the effective thickness of the fabric. A cotton or even a jute or glass-fiber blanket can be fluffed up temporarily to give equal original insulation (the reverse of conductivity) to that of wool. However, apparel must maintain its insulation value by maintaining its original thickness under the conditions of service. Hence not only is the bulk factor of a fiber important but its resilience is also. Because of the complexity of fabric constructions, fabric resilience, as represented by the recovery of bulk when a mass is crushed, is involved, as well as the resilience of individual fibers from deformation due to bending, twisting, and extension. Investigators are studying the exact principles controlling the maintenance of thickness, but for our purposes we can assume that all types of resilience play a part.

For clothing which is in contact with the skin, absorbency is also important. We have noted that the heat conductivity of water is very high relative to that of air. Even when conditions are not warm enough to induce sweating there is a constant formation of insensible perspiration. If this moisture is not otherwise disposed of, it forms as liquid water in the interstices of the fabric; hence the high insulation of air is replaced by the high conductivity of water, which is approximately 20 times that of air. This increases the body heat loss enormously. Under extreme conditions of cold this water will freeze at the point in the cross section of the garment where liquid water meets freezing temperatures. The frost point will gradually approach the inner surface, giving not only the low heat-resistance of ice and water, but actually putting still greater demands on the body for heat to melt the ice. The Eskimos are very careful to remove their clothes when inside so that sweat will not accumulate in their furs. Furthermore, they hang their garments outside to freeze when they are not wearing them. Before they put them on they beat them to shake off the frost and ice particles that may have formed from body moisture which accumulated during previous wearing.

In our civilian clothing we need resort to less rigorous practices. The moisture can be conducted away from the skin in several ways. It can move through the interstices of the cloth. In open weaves, up to 20% fiber density, there is little difference in the water-vapor permeability of fabrics made from different fibers because there are sufficient open spaces to allow free transmission. However, in fabrics of greater than 20% fiber density, the open spaces are too small for free movement of water vapor. Cotton, wool, and the cellulose fibers have sufficient absorptive capacity to allow the water vapor to actually travel through the fiber, thus allowing for removal of water from the skin regardless of the tightness of weave. The high absorbency of wool is therefore important in maintaining a high insulation value in wool fabrics.

In extremely cold climates water accumulation may act even more effectively in taking heat from the body. Assume conditions in which insensible perspiration is being formed in periods of relative inaction, or where sweating is induced temporarily by exercise. Assume that thick clothing is worn and that the temperature and vapor pressure at the outside surface of this clothing will cause condensation. The moisture formed on the skin is vaporized by the local, relatively high temperatures. The heat required for this vaporization is taken from the body. The water vapor travels through the fabric to the outside surface of the clothing. Here it is condensed, giving up heat in the process, away from the body, where it is of no value in maintaining body temperature. The condensed moisture is then sucked back towards the inside surface of the clothing by capillary action, which is aided by increasing temperature. This moisture is evaporated at the skin surface by heat taken from the body. The water vapor travels to the outer surface, where it again condenses on contact with the low temperature, gives its heat to the outer environment, and returns as liquid water to the inner surface. In effect, an efficient, closed system for transferring heat from the body to the outer environment is set up.

With highly absorptive materials, such as wool, the insensible perspiration may, within limits, be absorbed by the fiber without vaporization and resultant loss of body heat. However, when the accumulation of insensible perspiration or large quantities of active sweat exceeds the absorptive limits of the fiber, the above heat-transfer action is set up. But this action

is delayed or prevented to an extent which is directly proportional to the absorptive capacity of the fibers. The absorption capacity of wool gives it a superiority over other fibers in preventing such heat loss.

Convection

Convection is the loss or gain of heat due to air movement, either naturally induced from the difference in density of air at different temperatures or caused by drafts and artificial air circulation. The rate of heat exchange as a result of convection depends on the temperature difference between the surface of the skin or clothing and the surrounding air. It also depends on the rate of air flow. High air speeds cause greater amounts of air to be brought into contact with the surface; they also reduce the thickness, and, therefore, the insulating value, of the still air film lying next to the fabric surface. This air film is an important barrier to heat flow.

The outer surface of the clothing is, of course, fully exposed to outside air movement. There is also some convection of air inside the clothes, the air entering and leaving through open collars, cuffs, pants' legs, etc. Even when these openings are closed, natural convection currents are set up in any large spaces where air is entrapped inside. In order to cut down convection losses, it is important to close the openings in the garments, which, of course, are controlled by style. It is also important to keep the film of still air next to the surface of the fabric at maximum thickness. The hairiness of wool greatly assists in the maintenance of thick air films; so again the natural resilience of wool, especially in bending, is important. Furthermore, wool, relative to other fibers, retains a great deal of this resilience even when wet [10].

Radiation

Radiation is the transmission of heat to or from skin or fabric in the form of wave motion, similar to the transmission of light and sound. Radiation passes through the air without heating it. It can only pass between surfaces which can "see" each other. It cannot go around corners. The rate of transmission depends upon the fourth power of the temperature difference between the surfaces involved and upon the type of surface.

Surfaces vary in their capacity for emissivity. Skin, many textile surfaces, and black iron have high emissivity. A large part of their thermal heat can be transformed into radiant heat and can be transmitted. Highly polished surfaces and light-colored surfaces have low emissivity and radiate little heat.

Surfaces vary in their capacity to reflect or absorb heat which comes to them in radiant form. Surfaces with high reflectance have low absorptance and vice versa. Skin and most textile materials have low reflectance and high absorptance.

For a nude body under normal conditions of air and wall temperatures, as much as two-thirds of its total heat loss may be through radiation. However, as soon as there is rapid movement of air, the convection heat loss dwarfs the radiation heat loss. For a clothed body, where the outer temperature of the clothing is brought to a temperature which is much lower than skin temperature by the insulation of the clothing itself, a comparatively small proportion of the heat loss is through radiation. Under some special conditions, however, radiation losses may be important—for example, when temperatures of surrounding surfaces are extremely high or extremely low as compared with clothing temperature. Radiation may be an important influence on heat gain in direct sunlight or in the desert, where there is high reflection from the sand.

The high emissivity and high heat absorption properties of clothing can be modified by treatment of the fabrics with highly reflective materials such as metal powders. To be effective, however, the material must be present on the outside surface of the fabric or on surfaces between fabrics which are separated by air layers without mutual contact. The importance of control of radiation heat gain or loss is, of course, limited to the relative importance of radiation in the over-all heat change. Under most conditions radiation is not a controlling factor for clothed civilians.

Evaporation

Evaporation is the loss of heat through the vaporization of water or sweat. It will be seen that evaporation is an important factor in the heat-regulation mechanism.

The rate of evaporation is proportional to the sweat-production rate, the air temperature, and the amount and dryness of air coming into contact with the sweat.

In hot, humid atmospheres in the shade, maximum evaporation takes place when air is given free access to the body, as in the nude. Furthermore, cooling takes place directly on the skin, where it does the most good. In hot, dry air conditions, however, where a small volume of air will have a large evaporative capacity, clothing which entraps a small quantity of dry air by bellows action does not radically interfere with the cooling action of evaporation, and at the same time gives needed protection by decreasing radiation and convection heat gains.

Clothing in direct contact with the skin cuts down the amount of evaporation which takes place directly on the skin but at the same time gives a vastly increased area of evaporation. The absorbency of wool helps move the water to the surface of the clothing, where it has ready access to air, and the hairiness and resilience of wool, even when wet, insure the maximum evaporation area. A 14-oz. woolen fabric gives 527 square feet of accessible evaporative surface per square yard [3 (*a*)].

The absorbency of wool produces an inertia effect which slows down evaporation when it is first needed. On the other hand, by means of the same absorbency excess sweat is stored which might otherwise run off and be wasted. It is then available when later cessation of sweating (to avoid body dehydration) would otherwise cause the loss of evaporative cooling. The high absorption of wool prevents sudden chilling when exercise or other heat-producing activity ceases.

The absorbency of wool also has another value in an action which is practically the opposite of evaporation. Cassie [3] has shown that in going from the relatively dry, warm air of indoors to the relatively cold, moist air outside, the absorption of moisture by the wool actually serves to create heat. In going from a room with 45% relative humidity and a temperature of 64.4°F to the outdoors where the relative humidity is 95% and the temperature 41°F the heat of absorption in a 3.3-pound man's suit would be roughly equal to the amount normally lost by the body in 1½ hours.

Important Factors in the Protective Function of Clothing

Garments Worn Next to the Skin.—These would include bathing suits, underwear, socks, etc. In such clothing it is important to cut down the area of contact between fabric and skin. An area free from contact reduces the feeling of chill and clamminess when wet. A film of dead air space increases the insulation value. Absorbency is also important in removing insensible perspiration, the accumulation of which would cause heat loss in winter. In summer absorbency serves to remove sensible sweat to the outside of the clothing, where it is in direct contact with the moving air and gives greatly augmented surface area for evaporation. By means of absorption, sweat which might otherwise run off is stored for evaporation when sweating ceases.

Resilience is also important to maintain the thickness of the fabric and hence maintain its insulation against heat loss when the outside environment is at a low temperature or against heat increase when the outside air is hot.

Suits.—Elasticity, recovery from elongation, and fiber-mass resilience are necessary requirements for suits in order to maintain shape and to prevent creasing and wrinkling.

Outer Clothing, Sports Clothes, etc.—Again the high specific volume of wool, its bulking power, resilience, and crush-resistance are important in maintaining fabric thickness and insulation value. Good absorbency is also of importance.

Physical Characteristics of Wool

When we start to discuss physical characteristics we are usually too prone to talk about strength, probably because it was the first characteristic (aside from weight and length) that we could measure, and also because it is such an easy characteristic to visualize. As a matter of fact, fiber strength—that is, the load required to break a fiber—has little direct influence on the characteristics of the finished product, its resistance to wear, and its ability to provide service.

When dealing with the relationship between the strength of a fabric and that of the fibers from which it was made, the situation is complex and depends more upon other characteristics of the fibers and upon the controllable factors of weave and spinning. The weave and twist determine the amount of slippage between fibers in the yarn and between yarns in taking up a fabric load, and the weave also determines the relative lengths of yarn which might be involved in a given loading.

It is therefore not sufficient to consider the strength of a fiber alone. H. DeWitt Smith [13] discusses at length the necessity of considering characteristics in combinations rather than as individual entities.

TABLE I. TENSILE STRENGTH [15]* (GRAMS PER DENIER)

	Standard conditions†	Wet conditions
Nylon, high-tenacity	6.0–7.5	4.8–6.4
Acetate, saponified	7.0	6.0
Glass	6.3–6.9	5.4–5.8
Cotton [20]	3.0–6.3	20% above dry
Flax [20]	6.0	
Nylon, regular	4.5–5.5	3.5–4.7
Orlon	4.0–5.0	3.6–4.5
Viscose, high-tenacity	3.0–4.6	1.9–3.0
Vinyon N, stretched	3.5–4.5	4.2–4.5
Vinyon, high-tenacity	3.5–4.0	3.5–4.0
Jute [20]	3.8	
Vinyon N, stabilized	2.8–3.8	3.6–3.8
Viscose, medium-tenacity	2.4–3.0	1.2–1.7
Vinyon, regular	2.0–2.8	2.0–2.8
Polyethylene	1.0–2.5	1.0–2.5
Viscose, regular	1.5–2.4	0.7–1.2
Cuprammonium	1.7–2.3	0.95–1.25
Saran	1.4–2.3	1.4–2.3
Acetate, high-elongation	1.3–1.6	0.86–0.97
Acetate, regular	1.3–1.5	0.8–1.2
wool [20]	1.3	1.1
Vicara [8]	1.1–1.2	0.53–0.57
Vinyon, unstretched	0.7–1.0	0.7–1.0

* Numbers appearing in the table headings refer to the references at the end of this paper. They furnish the sources of data and apply to all of the individual items in the tables with the exception of the items that carry a numbered reference.

† Standard conditions are 70° F and 65% R.H.

He introduces the terms "tenacity" (strength per unit weight), "stiffness" (resistance to stretch), and "toughness" (the work required to attain a given stretched condition). As illustrations he uses the following adjectives for describing these characteristics: tenacity may range from "strong" to "weak"; stiffness can vary from "stiff" to "pliant"; toughness can range from "tough" to "yielding." Wool is very pliant, and weak but tough; silk is pliant, moderately strong, and very tough; flax is very strong but inextensible.

Tables I to V show the various fibers arranged on the basis of these characteristics. While wool is one of the weakest fibers, it will be noted that it stands at the midpoint in the list of fibers for toughness and near the top of the list for pliability. Furthermore, of the more pliable fibers—Vinyon (high tenacity), Vicara, and acetate (high elongation)—Vicara is both weaker and much less tough than wool. High-tenacity Vinyon and high-elongation acetate have greater toughness than wool, but high-tenacity Vinyon has lower elongation and none of these fibers have as good elastic recovery as wool has.

TABLE II. STIFFNESS [15] (GRAMS PER DENIER)

(In *increasing* order of *stiffness* and in *decreasing* order of *pliability*)

Vinyon, high-tenacity	2.4
Vicara [8]	2.8
Acetate, high-elongation	3.3
wool [20]	4.0
Acetate, regular	5.5
Vinyon, regular	7.7
Viscose, regular	11.1
Polyethylene	2–12
Vinyon N, stabilized	13.0
Cuprammonium	15.5
Viscose, medium-tenacity	16.6
Saran	20.0
Nylon, regular	24.0
Orlon	24.0
Viscose, high-tenacity	25.5
Nylon, high-tenacity	45.0
Vinyon N, stretched	49.0
Cotton [20]	57.0
Acetate, saponified	116.6
Jute [20]	185.0
Flax [20]	270.0
Glass	322.0

TABLE III. TOUGHNESS [15] (GRAM-CENTIMETERS PER DENIER-CENTIMETERS)

Vinyon, regular	3.3
Vinyon, high-tenacity	2.7
Saran	0.62
Orlon	0.61
Nylon, regular	0.5
Vinyon N, stabilized	0.48
Nylon, high-tenacity	0.45
Acetate, high-elongation	0.35
Polyethylene	0.3
Viscose, high-tenacity	0.22
Acetate, saponified	0.21
Viscose, medium-tenacity	0.21
wool [20]	0.2
Vinyon N, stretched	0.2
Viscose, regular	0.19
Vicara [8]	0.18
Acetate, regular	0.17
Cuprammonium	0.14
Cotton [20]	0.14
Glass	0.07
Flax [20]	0.06
Jute [20]	0.02

TABLE IV. ELONGATION AT BREAK (PERCENT) [15]

	Standard conditions*	Wet conditions
Vinyon, unstretched	100–120	100–120
Polyethylene	20– 60	20– 60
Acetate, high-elongation	45– 50	60– 70
wool [20]	40	
Vicara [8]	30– 35	30– 40
Vinyon, regular	20– 35	20– 35
Acetate, regular	23– 30	30– 40
Saran (oriented)	20– 30	20– 30
Vinyon N, stabilized	20– 30	25– 28
Viscose, regular	15– 30	20– 35
Nylon, regular	20– 25	21– 32
Saran (unoriented)	15– 25	20– 30
Orlon	16– 21	16– 22
Vinyon, high-tenacity	18– 20	18– 20
Nylon, high-tenacity	14– 20	
Viscose, medium-tenacity	12– 20	17– 30
Cuprammonium	10– 17	17– 33
Viscose, high-tenacity	9– 17	14– 20
Vinyon N, stretched	9– 11	8.5–9.5
Cotton [20]	6– 7	
Acetate, saponified	6–6.5	
Glass	3– 4	2.5–3.5
Flax [20]	1.6	
Jute [20]	0.8	

* Standard conditions are 70° F and 65% R.H.

TABLE V. ELASTIC RECOVERY (PERCENT) [15]

	Recovery after stretching 4% of original fiber length	Recovery after stretching the indicated % of original fiber length
wool [19]		100 at 30%
Nylon, regular		100 at 8%; 91 at 16%
Vinyon N, stabilized		100 at 0.5 g. per den.
Glass	100	
Vicara [8]	99.5	90 at 20% (wet)
Saran	95 (slow)	
Viscose, medium-tenacity		97 at 2%
Orlon	84 (instant)	97 at 2% (instant)
Polyethylene		90–95 at 5% (slow)
Vinyon, regular		90 at 80% load
Cuprammonium	17–75	
Vinyon N, stretched		76 at 1.5 g. per den.
Viscose, regular	30–74	58 at 14%
Viscose, high-tenacity		70–100 at 2%
Acetate, saponified		100 at 1.2%; 60 at 2.4%
Acetate, regular	48–65	29 at 14%

Work is just beginning on the engineering relationships of these characteristics in fabric constructions and their dependence on the fiber characteristics such as those discussed in Tables I-V. We must wait for the results of this work before we can go into more detail. However, it is apparent that wool possesses a highly desirable combination of tenacity, pliability, toughness, and elongation.

In the above discussion of the various desired qualities in fabrics, the importance of resilience has been emphasized repeatedly. It is important in resisting crush, in enabling wool garments to lose wrinkles when they are hung, in maintaining fit, in maintaining thickness (and hence insulation value), in giving the resilient, hairy surface that cuts down the area of contact with the skin, in giving wool fabrics their soft and warm feel, and in providing summer suits of good covering power with light weight and air porosity.

Resilience may be measured in several ways. It can represent recovery from elongation (Table V) and the recovery of mass volume after compression (Table VII). As noted in these tables, wool stands at the top of the list in recovery from elongation and in recovery from compression. For example, according to von Bergen [19] wool will recover 100% of its initial length after stretching to 30% of its original length. Regular nylon will recover 100% after an 8% stretch and 91% after 16%. Glass has excellent recovery but it can only be stretched 3% to 4% without breaking. (See Table V.)

In recovery from mass compression, wool—even the finer, soft wools which are not noted for their resilience—has resilience superior to that of the other fibers, recovering 55.8% of its volume after compression in a mass taken at 0.001 pound per square inch to 1.0 pound per square inch pressure. This compares with a recovery of 53% for waste nylon and 52.2% for degummed silk. (See Table VII.)

Compressibility is an indication of the apparent softness to the touch. Under compression, in going from 0.001 to 1.0 pound per square inch pressure, wool will lose 85% of its volume (of which it recovers 55.8%). Cellulose acetate will lose about the same amount on compression but will recover only

TABLE VI. COMPRESSIBILITY (PERCENT) [11]

	Volume lost (%) when compressed in the mass taken at 0.001 lb. per sq. in. to 1.0 lb. per sq. in. pressure
WOOL, 70's sliver	85.0
Cellulose acetate	84.9–85.3
Cotton	80.8–84.0
Silk, degummed, first draft	77.0
Viscose, staple	69.2
Nylon, waste	67.7

TABLE VII. RESILIENCE [11]

	Volume recovered (%) after compressing a mass taken at 0.001 lb. per sq. in. to 1.0 lb. per sq. in. pressure
WOOL, 70's sliver	55.8
Nylon, waste	53.0
Silk, degummed, first draft	52.2
Cellulose acetate	44.4–44.6
Cotton	37.7–39.1
Viscose, staple	30.7

about 44.5% after release, and cotton will lose 80% to 84% of its volume and recover only 37% to 39%. (See Tables VI and VII.)

The above discussion of resilience is obviously extremely simplified. It is only when we go into still greater detail and delve deeper into the complexities of fiber behavior that we can completely explain why wool gives the performance that sets it apart from other fibers. Hoffman [7] has provided a most interesting discussion of resilience in which he points out that although quartz, rubber, and wool are all highly resilient, yet their behavior is quite different. He points out that much of this difference is tied up with the great influence of the time factor in wool behavior. Hamburger [6] has worked out an elastic performance coefficient to represent this time effect as applied to fiber tests.

Quartz has a high modulus and a low time effect. Rubber has a low modulus and low time effect. Wool has a high modulus and a high time effect. Hoffman describes the differences in work recovery at different degrees of extension. For example, at 0.5% extension wool has 94% work recovery as compared with 82% for nylon, while at 5% extension wool has only 29% recovery as compared with 75% for nylon. Wool has a dual nature. It is fairly stiff and springlike for short loading times and low strain, but it is increasingly compliant at longer loading times and higher strains. This explains why a good woolen fabric can be described as crisp yet soft. This is in direct contrast with the so-called "dead" fabrics, which are either too limp or too harsh depending upon the weight of material used.

TABLE VIII. SPECIFIC VOLUME [11]

	Specific volume (cc. per g.) taken at ½ lb. per sq. in. pressure
Viscose, staple	13.1
Cellulose acetate	10.6–11.1
Silk, degummed	10.8
Cotton	9.0–10.3
WOOL, 70's sliver	9.7
Nylon, waste	7.9

The importance of absorbency has already been emphasized. This characteristic enables wool fabrics to retain their warmth by preventing the accumulation of moisture. It helps pass sweat to the outer surfaces for evaporation. Wool has the highest absorption of the fibers studied except cuprammonium

TABLE IX. REGAIN (PERCENT ON DRY WEIGHT OF FIBER)

	77° F and 95–97% R.H.	70° F and 65% R.H.	77° F and 40% R.H.	77° F and 10% R.H.	60% R.H.	Water absorbency
Cuprammonium	27 [15]	12.5 [15]				
Viscose	26.1 [16]	13 [15]	8.7 [16]	3.8 [16]		
WOOL	25.6 [14]		9.65 [14]	4.15 [14]		
Vicara	16–18 [8]	10 [8]				
Cotton	15.6 [17]		4.7 [17]	2.0 [17]		
Acetate	13.0 [14]	6 [15]	3.2 [14]	0.9 [14]		
Nylon	6.2 [5]	3.8 [15]	2.3 [5]	1.1 [5]		
Orlon	2 (78° F) [15]				0.9 [15]	
Vinyon N		0.0–0.5 [15]				1.0 [15]
Glass		None [15]				0.3 [15]
Vinyon		0.0–0.5 [15]				0.1 [15]
Saran		None [15]				0.1 [15]
Polyethylene		None [15]				0.1 [15]

and viscose rayon (Table IX). At 95% relative humidity wool will absorb 25.6% of its dry weight in water as compared with 15.6% for cotton, 13.0% for acetate, and 6.2% for nylon, the last figure obtained at 97% relative humidity. Viscose rayon will retain 26.1%, but viscose has only 30.7% mass resilience and 30% to 74% elastic recovery after a 4% stretch. Viscose also has limited elongation and is nearly three times as stiff as wool. Cuprammonium is nearly four times as stiff as wool, is much less tough, has low elongation, and poor elastic recovery.

The specific volume (cubic centimeters per gram) of masses of fibers is also of interest (see Table VIII). It indicates how the fibers will pack, or the volume occupied by randomized fibers. The figures given in Table VIII were taken under ½ pound per square inch pressure to eliminate some of the variables that depend entirely upon the way the test fibers may have been handled. The specific volume may be taken as a rough estimate of the thickness obtainable from a given weight of fabric. As the heat insulation value for many types of fabrics is dependent upon thickness, it also gives an indication of the relative heat insulation per unit weight. Obviously, special constructions may be designed to make a fabric more or less lofty with some independence of these random-volume figures. However, we have little interest in the insulation value of a fabric as it is first manufactured. A fabric must retain its insulation in actual service; specific volume figures must therefore be considered practical only in connection with associated compressibilities and resiliences.

Table VIII shows that viscose has the highest specific volume and that acetate, silk, and cotton have higher specific volumes than wool. However, cotton and acetate have very high compressibility and poor recovery, and viscose has very poor resilience.

Wool fiber has one other important characteristic which is exceptional among the common apparel fibers. Only a few rare fibers have felting properties similar to those of wool, yet this property gives a most valuable asset in obtaining the refinements of fit and the highly prized finishes in jerseys, gabardines, serges, and other beautiful materials. It also gives improved wear, resistance to snagging, firmness of handle, and wind-resistance without impedance of the transmission of water vapor.

Felting, as the cause of loss of dimension in washing, can be controlled by suitable shrink-resistant treatments which can be adjusted to give the combination of washableness and finishing quality that are desired in a particular garment designed for a particular use.

Unlike many apparel fibers wool does not support combustion or burn with a flame. When exposed to an outside source of ignition, the wool fiber will merely char and shrivel, leaving a semiprotective deposit of ash. Even in highly napped fabrics the individual fine fibers when exposed to an open flame simply char, without supporting continued combustion. The heated fiber does not melt and drop off to spread combustion or cause burns on adjacent surfaces.

In drawing upon the literature for data on the natural fibers it becomes apparent that there is a great lack of comparative information on the physical characteristics of all fibers as determined under identical conditions of tests. There is particular need for additional information for all fibers on the immediate elasticity, primary creep, and secondary creep under commonly encountered atmospheric conditions and under a variety of conditions of load. There is also need for a more complete compilation of the information about fiber and fabric characteristics and their interrelationship. It is encouraging to note that work in this direction is already under way. We look forward to much more complete and definitive discussions in future publications.

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Book Reviews

Developments in the Wear Resistance of Textiles and Related Papers Published in Germany during World War II. Washington, D. C., Office of Technical Services, U. S. Department of Commerce, 1950. 368 pages; illustrated. Price, $5.00.

This is a collection of selected papers, translated and compiled at the request of the Chief Quartermaster, U. S. Army European Command.

During the war the Germans were desperately pressed by shortages of materials, and, under the urgent necessity of finding ways to avoid unnecessary losses in use, a tremendous amount of work was done in the fields covered by this report. The papers are a selection of the more significant articles which it was felt would not become generally available to American research workers.

Some of the papers represent hitherto unpublished manuscripts and others appeared in *Melliand Textilberichte* between 1939 and 1947. Five main topics are covered: evaluation of the serviceability and wear-resistance of textiles; chemical and photochemical degradation of cellulose; investigation and classification of textile fiber properties; fiber structure and reactability of fibers; and resistance to water and shrinkage.

This work of the Germans is worthy of careful study by technologists in the industry. In any future crisis we might find ourselves in a similar position and fabric improvement along these lines may mean the difference between success and failure.

The Fundamentals of Detergency. William W. Niven, Jr. New York, Reinhold Publishing Corporation, 1950. 256 pages. Price, $5.50.

(Reviewed by William P. Utermohlen, Jr., The Permutit Company, Birmingham, New Jersey)

This book was written under the sponsorship of the American Institute of Laundering, with the objects of bridging the gap between general and specialized information on detergency and of showing gaps in the basic knowledge and inconsistencies in the published data in this field.

Part I is a discussion of the fundamental aspects of detergency, in which are considered such topics as: nature and properties of detergents; chemistry, surface activity, and actions of unbuilt detergent solutions; properties of builder solutions; and influence of builders on the nature and actions of detergent solutions. Part II discusses some practical consid-

erations involved in the laundering process, under headings including: soils and soiling; separation of soil from fabric; dispersion of soil in detergent solutions and stabilization of such dispersions; summarization of detergent action; and comparison of present detergent knowledge and present washroom practice. Listing and discussion of specific detergent agents have been purposely avoided.

In the field of detergency authoritative summarizing books are badly needed, and it is therefore unfortunate that this book has a number of serious shortcomings. The principal part is essentially a review of the literature on detergency, and many sections rely too heavily upon non-recent source material. The section on emulsification has only one literature reference later than 1923, and the section on electrical phenomena in detergency has only one reference after 1929—to cite but two examples of the author's failure to give adequate recognition to recent work. The chapters on the influence of builders on detergent solutions were somewhat confusing and difficult to comprehend. All of the chapters in Part II are sketchy and appear to have been written quickly, as if against a deadline. Little or no mention is made of a number of important topics of current interest covered in recent papers, including: the relation of the solubilizing power of a surface-active material to its use as a hydrotropic agent, wetting agent, or detergent; improved quantitative evaluation of the soil on textiles or metals before and after washing; and the use of sodium carboxymethylcellulose as an additive in textile detergents to reduce soil redeposition. The general subject of foaming is considered at length, but the methods of foaming measurement, the accuracy of these methods, and the application of foam fractionation to eliminate the minima in some surface tension-concentration curves are not discussed. The contact-angle theory is accepted and used without question, although a number of workers doubt its validity. Some of the statements in the chapter on soils and soiling are contrary to this reviewer's experience.

On the favorable side, the book is attractive typographically, and no printing errors were noted. The important work of McBain and his coworkers is adequately covered. The occurrence of sharp changes in many surface-active properties at a similar narrow range of concentration and the relation of these changes to micelle formation are well presented and summarized. The book could give much useful information to one about to begin research in detergency, provided the reader realized that it is not up to date in many important fields.

Fundamentals of Synthetic Polymer Technology in Its Chemical and Physical Aspects. R. Houwink. New York, Elsevier Publishing Company, 1949. 248 pages. Price, $3.75.

(Reviewed by G. H. Fremon, Union Carbide and Carbon Corporation, South Charleston, West Virginia)

This volume presents a highly condensed review of virtually all aspects of all high polymers. The chemistry of polymerization; the physics of macromolecules; methods of testing plastic materials in America, Great Britain, and Europe; basic processes for fabricating resinous materials; the manufacture of each of the major types of high polymers; and the economics of the synthetic rubber, plastics, and synthetic fibers industries—all of these receive attention. Needless to say, the coverage is not very thorough: as an example, only 19 pages are devoted to the technology of polymers based upon cellulose—raw materials, preparation of derivatives and manufacture of lacquers, molded products, cellophane, and the rayons.

The present work differs from the usual introduction to the field of high polymers in the proportion of space devoted to the physics and physical chemistry of polymerization and the behavior of macromolecules, and in the array of fundamental phenomena mentioned. The bibliography pertaining to the field of high-polymer science is not extensive, but it is nevertheless a better guide than one finds in most "once-over-lightly" treatments.

In other respects, however, the comparison is not so favorable. The discussions of industrial activities are so condensed that this reviewer questions their usefulness; the language is often awkward and, in places, obscure; and many of the charts and tables require a relatively high degree of concentration of attention on the part of the reader.

The educated layman interested primarily in acquiring a nodding acquaintance with the whole high-polymers field may therefore find this book less satisfactory than others already on the library shelf; but if, on the other hand, he is looking primarily for a brief introduction to the field of high-polymer science, the first three chapters may serve his purpose adequately.

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